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Analysis of delayed sea breeze onset for Fort Ord prescribed burning operations

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THESIS

ANALYSIS OF DELAYED SEA BREEZE ONSET FOR FORT ORD PRESCRIBED BURNING OPERATIONS

by

Dustin D. Hocking

December 2015

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The U.S. Army conducts prescribed burns at Fort Ord, in Monterey County, California, and is reliant upon forecasting a delayed sea breeze for successful smoke management. This has been previously associated with opposing synoptic scale flow, static stability, and weakened thermal gradients. Evolution of the sea breeze in the complex coastline and topographic structure of the Monterey Bay area is the focus of this study.

The CFSR and 12 km NAM combined with local observations in a multiquadric data assimilation system was used to characterize synoptic and mesoscale flow evolutions. Eight case studies were analyzed to better understand background synoptic flow and mesoscale response, characterize primary sensitivities, and develop "rules of thumb."

All case studies had delayed sea breeze onset until approximately 2000 UTC. A 5 knot delayed sea breeze is triggered by a 5° cross-sectional thermal gradient in the presence of a 2–3 knot offshore synoptic scale component over Fort Ord regardless of synoptic flow strength or direction. A weaker 2 knot delayed sea breeze developed when strong static stability reduced vertical motion or in the absence of a background cross-coast thermal gradient. These factors suggest key forecast parameters to anticipate sea breeze delay effectively lengthening a burn "window."

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ANALYSIS OF DELAYED SEA BREEZE ONSET FOR FORT ORD PRESCRIBED BURNING OPERATIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

BRAC	Base Realignment and Closure
CARB	California Air Resources Board
CFSR	Climate Forecast System Reanalysis
CONUS	Continental United States
DTSC	Department of Toxic Substances Control
EPA	Environmental Protection Agency
FORA	Fort Ord Reuse Authority
GKS	Graphical Kernel System
MEC	Munitions and Explosives of Concern
MRA	Munitions Response Area
MQ	Multiquadric
NAM	North American Model
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NPL	National Priorities List
NPS	Naval Postgraduate School
NWS	National Weather Service

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Furthermore, I owe many thanks to various supporting personnel. First, Bob Creasey continually answered my requests for archived data with consummate professionalism, providing the information in an efficient and accurate manner allowing me to meet all required timelines. Additionally, my classmates helped to make meeting the challenging course load and demanding requirements of the Meteorology and Oceanography (METOC) program feasible, and I am thankful for their assistance and support. Specifically, I would like to mention Mike Papa, who was always there when needed and is a great hunting companion, as well as Tucker Freismuth, whose conversations were memorable and provided an 'Ohio Valley' flare to the NPS experience. Thank you, gentlemen, for your contributions.

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I. INTRODUCTION

The former Fort Ord in Monterey County, California, previously also known as Gigling Reservation, and Camp Ord, was established in 1917. Encompassing roughly 28,000 acres, the largely undeveloped land area was first used to train infantry soldiers in support of World War I, and continued in this mission through the first Gulf War (Stahl 2008), housing the 7th Infantry Division of the Army. Throughout its history, much of the open land in Fort Ord was utilized as an artillery and firing range (Stahl 2008). In its prime, the base was home to over 50,000 soldiers training to be the tip of the spear for the military fighting battles around the world (Stahl 2008). However, following the post-Cold War era, the Base Realignment and Closure (BRAC) Commission of 1988 sought to downsize the military base footprint. Thus, from 1990 to 1991, Fort Ord was placed on the National Priorities List (NPL) by the Environmental Protection Agency (EPA) as a federal Superfund site and identified for closure (Duymich 2012) due to groundwater contamination from multiple sources such as underground petroleum leakage, landfills, and ordnance ranges (Stahl 2008). Fort Ord was closed in 1994, leaving behind decades of dangerous ordnance strewn throughout the depths of the grounds, in a sense providing its own history lesson from previous war training exercises (Duymich 2015). Once the shelling stopped, however, the vegetation on the firing ranges rebounded, making ordnance removal difficult and dangerous. In the nearly 20 years since it closed, the former base had remained off-limits to all but a few official personnel. This isolation had the unintended effect of preserving valuable plant and animal species—some that had been lost to development elsewhere, and others unique to Fort Ord—which complicated the ordnance removal situation further. On April 20, 2012, in response to concerted preservation efforts by citizens, and local and state elected officials, the President of the United States, Barack Obama, authorized Proclamation 8803, which established the Fort Ord National Monument to preserve this historical landscape and its natural features (Obama 2012).

In the aftermath of its closure, the Army along with the EPA and numerous other federal, state, and local organizations developed a plan for removal of ordnance at Fort

Ord in order to turn the grounds over from military to civilian control, with oversight from the Fort Ord Reuse Authority (FORA) (Youngblood et al. 2008). The cleanup process, projected through 2021, will cost the Army approximately $187 million (Stahl 2008), with the majority of those funds allocated for ordnance removal. The Army expediently removed ordnance from 6,000 acres (Stahl 2008); however, the roughly 6,560 acres referred to as the Impact Area Munitions Response Area (MRA) still remains, containing the majority of ordnance ranging from small arms casings to hand grenades and even larger 60mm mortars (Figure 1). While these munitions are old in age, they still remain extremely dangerous, as evident from various previous news articles in the *Monterey Peninsula Herald*, dating from 1943 through 1976, depicting numerous serious injuries and deaths to the civilian population who ventured into the areas for public recreation (Duymich 2012). Thus, the MRA is currently strictly marked with only those areas cleared as permissible for public traffic. In addition to this, the MRA happens to be home to approximately 90% of the remaining Central Maritime Chaparral in the world, the conservation of which is of vital interest to the habitat (Figure 2). As a result, vegetation and munitions clearance options were studied and investigated by the Army and EPA with assistance from the California Department of Toxic Substance Control (DTSC) to examine the best possible solution (Youngblood et al. 2008).

Figure 1. Image depicting numerous munition types post prescribed burn

Source: Duymich, C., 2012: Fort Ord Prescribed Burn Program 2012. Accessed 20 October 2015.

Figure 2. Various maritime chaparral species local to Fort Ord

Source: Duymich, C., 2012: Fort Ord Prescribed Burn Program 2012. Accessed 20 October 2015.

After considering the possibilities and illustrating them through the Draft Final Technical Memorandum–Evaluation of Vegetation Clearance Methods Ordnance and Explosives Remedial Investigation / Feasibility Study (RI/FS), Former Fort Ord as well as Final Track 3 Impact Area Munitions Response Area (MRA) Munitions Response RI/FS, Former Fort Ord (Duymich et al. 2015), the Army and EPA agreed upon utilizing the Technology-aided Surface MEC Remediation, with Subsurface MEC Remediation in Selected Areas and Land Use Controls as the solution. This process encompasses prescribed burns to clear vegetation in the respective area(s) in order to access, remove and clean up the munitions and explosives of concern (MEC). Specifically, this process (Youngblood et al. 2008) requires a phased approach in which approximately 100-acre units may be burned at one time with no more than 800 acres burned per year. In doing so, a painstaking multitude of steps must be taken in preparation of the site as well as in the post-deployment phase of the operation. These actions include biological monitoring, which occurs before, during, and after the process to ensure vegetation recovery is in accordance to guidelines. Through this process, prescribed burns have proved to bring positive effects to the habitat such as resurgence in threatened and endangered species, habitat rejuvenation, and an abundance of new vegetation or “fire followers” (Duymich 2012). In addition, mastication is essential in order to provide containment lines resulting in firefighter safety. These lines must be at least greater than 100 feet wide around the respective area and are site-specific. These buffer areas as well as fuel breaks and access roads provide logistical support for required equipment and vehicles in the prescribed burning process (Youngblood et al. 2008). To be successful, these actions and many others leading up to, during, and after the respective prescribed burn(s) must be coordinated through, and are dependent upon not only the military but also the actions of various civilian and federal organizations within and outside the local area.

Specifically, and thus the motivation behind this research, the meteorological conditions are the greatest factors to either help or hinder the above-mentioned process. Successful smoke management is directly associated with light winds and strong vertical mixing, both of which are strongly affected by the local sea breeze. The lead meteorologist, Dr. Wendell Nuss, Chairman, the Department of Meteorology at the Naval

Postgraduate School (NPS), along with input from the Monterey National Weather Service (NWS) and the California Air Resources Board (CARB), is tasked with providing the weather outlook and forecast in support of prescribed burns (Duymich et al. 2015). This support is depicted through the Fort Ord Prescribed Burn Weather Outlook and Forecast website (http://met.nps.edu/~nuss/fort-ord.html) created and maintained by Dr. Nuss. The resultant outlook is created from numerical model forecasts and checked against five specific weather parameters, which will be categorized in Chapter II, in order to generate a color-coded stoplight chart forecast for seven days. In addition, Dr. Nuss, with decades of local meteorology experience, adjusts the forecast if needed with the result also depicted in stoplight form containing additional reasoning and discussion as well as supporting weather products. Through the previous work of Taylor (1998) and Duvall (2004), the vital characteristic in prescribed burn forecasting for determining whether a window of time to burn will become available relies on the ability of the forecaster to accurately determine when the local area sea breeze front onset will be delayed from the typical mid-morning into the afternoon timeframe.

Therefore, with millions of dollars invested by the Army (Stahl 2008), as well as a large logistical footprint required, protecting nearby communities surrounding Fort Ord with proper smoke management through accurate prediction of the timing of the onset of local sea breeze is vital.

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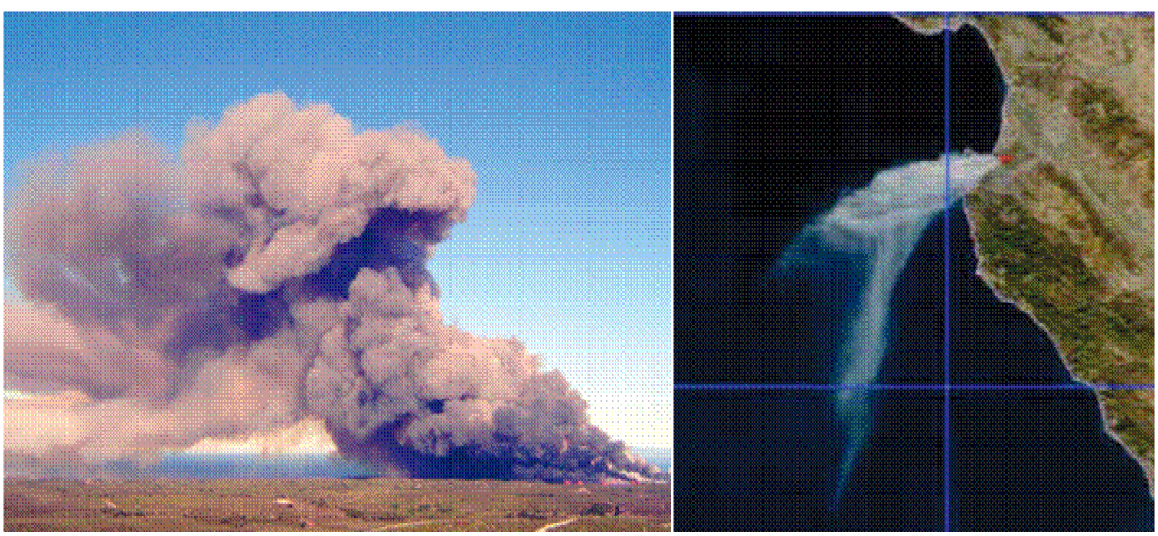
II. BACKGROUND

A. PRESCRIBED BURN: OCTOBER 24, 2003

On October 24, 2003, approximately 500 acres were ignited by the U.S. Army to burn off vegetation in order to expose ordnance for safe removal from the property (Bakan 2004). While the weather parameters of mixing height, wind direction, wind speed, temperature, and relative humidity were in adherence to standards up to and during ignition, subsequently, the fire raged out of control, burning 1470 acres and billowing smoke at low altitude into the surrounding population centers (Figure 3; Bakan 2004). While the fire spread only to adjacent Fort Ord land identified for a future prescribed burn before it was brought under control—and in the process exposed ordnance not previously known to be in the area—the overwhelming residents' outcry against the low-altitude smoke, the resultant public relations setback, plus cost overruns to the Army to the tune of $364,579, only exemplify the necessity to better understand the weather dynamics of the region (Bakan 2004).

Figure 3. Imagery from October 24, 2003 uncontrolled prescribed burn at Fort Ord



Source: Bakan, M., 2004: Fort Ord Prescribed Burn Review, Fort Ord BRAC Office CommunityBulletin#7,8pp.

The initial announcement for the October 24 prescribed burn was made on October 21, resulting in deployment of all of the logistical and firefighting crews to the area, as well as notifications to the public to inform the Monterey Bay area of the pending operation. Once the decision is made, continuous weather monitoring is conducted for the region to ensure necessary weather parameters (as denoted in Table 2) are within suitable limits. Dr. Nuss, Army officials, and officials from the EPA, California DTSC, and the California Air Resources Board continued this process right up until ignition of the burn. Of note, the National Weather Service had issued a fire weather warning to the region; however, the Red Flag Warning excluded regions along the immediate coast (Bakan 2004). As depicted in the after action weather comparison chart in Table 1, all weather parameters were within the "preferred" limits except for the mixing level, which hovered around the minimum requirement. This low mixing height of approximately 1,000-ft upon ignition prevented the resulting smoke from ascending vertically in the atmosphere, instead causing it to blow horizontally (southwesterly) into the population center of the Monterey Peninsula. Further investigation into the NPS Profiler analysis on October 24, 2003 also displayed the required mixing height of 1,500 ft delayed into midday vice morning (Figure 4). The delayed sea breeze onset (1400 PST) provided the initial favorable conditions; however, early morning low-level enhanced flow decreased the mixing height until 1100 PST. This resulted in a deteriorated prescribed burn window from 5 hours to 3 hours. Therefore, the resultant smoke did not ascend vertically, but was forced horizontally, affecting surrounding populated neighborhoods and further exposing the necessity for improved smoke management.

Table 1. Comparison of prescribed and actual weather conditions

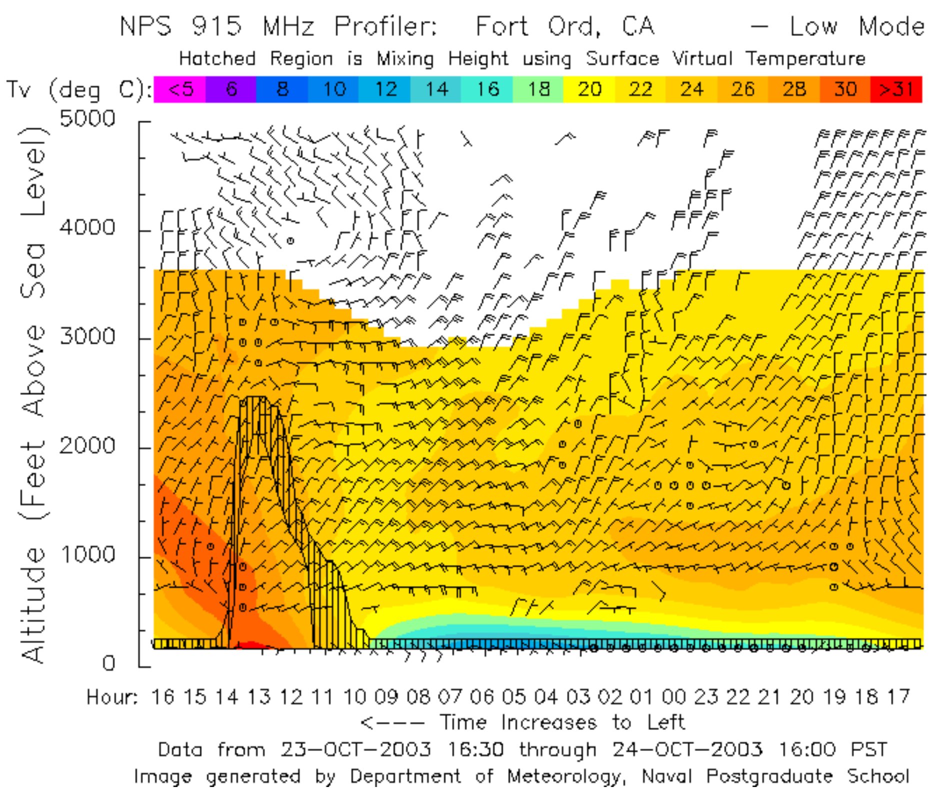
COMPARISON OF PRESCRIBED AND ACTUAL WEATHER CONDITIONS

(Source of information is Draft MRS-Ranges 43-48 Prescribed Burn After- Action Report, April 2004)

Weather Conditions		Prescription		October 24
Sky		Acceptable	Preferred	(9:06 AM – 11:00 AM)
		Clear or clear to scattered cumulous	—	Clear
Wind Direction and Speed	Morning	Direction 40-140°, Wind speed: 0-15 mph	Direction: 70-120°, Wind speed: 5-10 mph	Direction: 68-78° (Southwest-west) Wind speed 6-15 mph
	Afternoon	Direction 240-40°, Wind speed: 0-15 mph	Direction 270-40°, with periods of calm to light winds with variable directions	NA
Temperature		55-85° F	65-80° F	68-76° F
Relative Humidity		10-60%	14-40%	23-30%
Late morning mixing level		A mixing depth of 1,500 ft. within 2 hours of ignition		10:00 AM = 1,000 feet 12:00 PM = 1,500 ft 1:00 PM = 2,500 ft

Source: Bakan, M., 2004: Fort Ord Prescribed Burn Review, Fort Ord BRAC Office Community Bulletin #7, 8 pp.

Figure 4. NPS Profiler for Fort Ord on October 24, 2003



Hatched area depicts the low mixing heights until midday. Source: Monterey Area Environment, 2015: NPS 915MHz profiler at Fort Ord mixing height: 2003. Accessed 06 April 2015

The unintended result of the October 24, 2003, prescribed burn highlighted the necessity to dissect the localized weather patterns and behaviors in relation to the synoptic scale flow, and better understand how dynamic the Monterey Bay and Fort Ord regions are even within the 24-hr period—specifically the few hours leading up to burn operations. While reasons for the uncontrolled fire and enhanced smoke dispersion were not solely due to weather parameters but also firefighting procedures as noted in Bakan (2004), two specific lessons learned were noted in the review:

- The ability to make reliable weather predictions even 48 hours before a fire is very limited.
- Wind should be measured at higher elevations, not just on the ground, to more accurately predict where smoke will go.

The Fort Ord Prescribed Burn Weather Outlook and Forecast website provides a seven-day forecast outlook. This stoplight chart highlights a respective potential burn day as green, thus providing a "window" for which to conduct a prescribed burn. Once the window is identified, Dr. Wendell Nuss contacts the Prescribed Burn Manager who in turn contacts the various supporting project meteorologists, operational personnel, and logistical personnel to begin coordination (Duymich and Coauthors 2015). As the operation nears, specifically within the 48-hr to 24-hr timeline, the prescribed burn weather parameters (Table 2) are continually monitored and reported. As noted in Duymich et al. (2015), these parameters are interactive and dynamic; thus, having one or more parameters exceeding limits may not necessarily cancel the operation if smoke behavior would still satisfy fire management preferences. Additionally, as more prescribed burns are conducted and lessons are learned, the weather parameters are adapted. For example, the October 24, 2003, Fort Ord prescribed burn, as denoted above, resulted in including transport wind speed into the weather parameters. One similarity, however, among all successful burn operations is the delayed onset of the sea breeze; thus, for this study; its evolution is of primary concern. Specifically, the goal is to exploit a 4–6 hour window with a mixing height above 1,500 feet highlighted by a climatological sea breeze delayed at least 2 hours to best support successful smoke management.

Table 2. List of prescribed burn weather parameters

PRESCRIBED BURN WEATHER PARAMETERS		
Environmental Variables	**Ideal or Preferred**	**Maximum Acceptable**
Surface Wind Speed	Calm - less than 5 knots	Gusts not to exceed 10 knots
Surface Wind Direction	Any direction if calm	SE Counter Clockwise N to W
Transport Wind Direction (layer > 1,000-ft)	Any direction if calm	SE Counter Clockwise N to W
Sky Conditions	Clear Skies and no fog	Mid to High Clouds
Transport Wind Speed (< 1,500-ft)	< 10 knots (Sustained)	
Transport Wind Speed (> 1,500-ft)	< 20 knots (Sustained)	
Mixing Height	> 1,500-ft	
Temperature	45°F - 90°F	
Relative Humidity	20% - 80%	

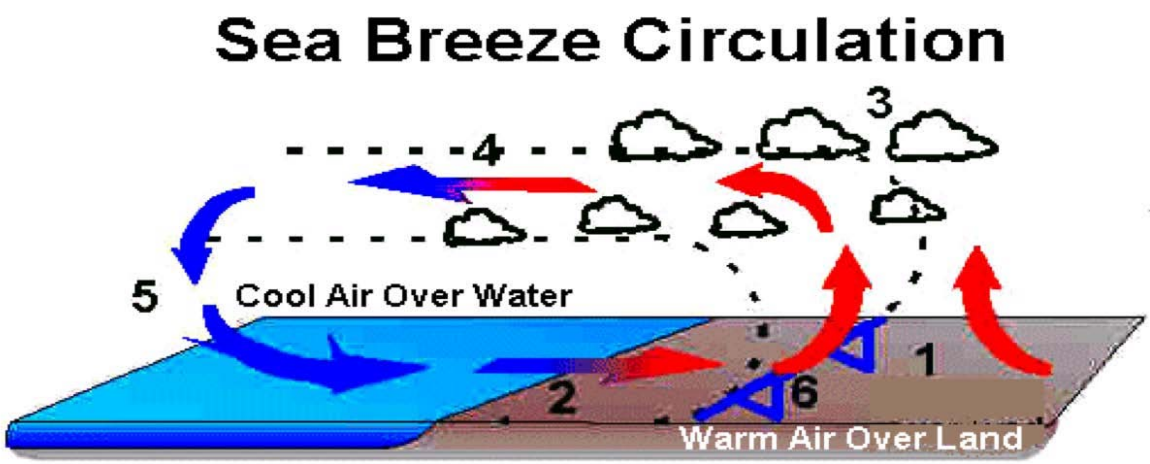
Source: Duymich, C., 2012: Fort Ord Prescribed Burn Program 2012. Accessed 20 October 2015.

B. BASIC SEA BREEZE CIRCULATION

Smoke management for Fort Ord Prescribed Burns is most successful through understanding the basic and specific Monterey Bay sea breeze structures and their impact on low-level winds and mixing height. The sea breeze is a thermal gradient driven mesoscale circulation resulting from physical processes active at the coastline (Wallace and Hobbs 2005). To best understand this phenomenon; one must first consider differences in thermal conductivity between the land and ocean. The land's lower thermal conductivity results in a greater response to solar radiation, thus heating the land surface at a faster rate than the ocean (Nuss 2003). The resultant warmer land surface creates the necessary horizontal thermal gradient to initiate the sea breeze circulation. Thus, the localized low pressure over land and high pressure over the ocean generates convergence at the surface vertically transporting the warmer air aloft creating offshore flow in the higher levels (Wallace and Hobbs 2005). As a result, in response to the offshore flow at

higher levels, air descends over the ocean in order to replace the air due to the surface level onshore flow (Figure 5). Additionally, the strength of the sea breeze is proportional to the magnitude of the respective thermal gradient (Nuss 2003). The process is reversed in the late afternoon or early evening to create a land breeze circulation resulting from a reversal in the thermal gradient. While the basic sea breeze is well understood, numerous factors alter the basic circulation to delay, strengthen, or weaken the circulation. These modifying influences include the synoptic-scale background flow, stability, clouds, coastline shape, and topography, which must be considered to better characterize sea breeze circulations in a particular region (Nuss 2003).

Figure 5. Schematic of coastal flow resulting in sea breeze circulation



Source: Nuss, W., 2003: *Coastal Meteorology*: Course Notes for MR4240. Department of Meteorology, Naval Postgraduate School, Monterey, California, 68 pp.

C. MONTEREY BAY SEA BREEZE CHARACTERISTICS

Previous Monterey Bay sea breeze studies shed light onto the unique features influencing the localized sea breeze. Specifically, topography, synoptic flow, and stability have been identified as key contributors that characterize the Monterey Bay sea breeze onset. Wexler (1946) first classified sea breezes based on background flow characterizations into either gradual growth, resulting from calm or gradual winds, and

frontal, resulting from an offshore gradient wind (Taylor 1998). Round (1993) utilized the NPS Profiler from Fort Ord expanding the work of Wexler (1946) into the specific Monterey Bay categories of gradual development, clear onset, frontal, double surge, unclassifiable, and no sea breeze (Taylor 1998). Round (1993) also found the Monterey Bay sea breeze onset develops most frequently around 1000 PST with strongest intensity from April to June (Knapp 1994). Additionally, Knapp (1994) further validated these results confirming a 1000 PST sea breeze onset with a climatological weakening of intensity through September. Knapp (1994) also defined the large-scale synoptic flow patterns influencing the Monterey Bay as a Ridge, Trough, Gradient, and Miscellaneous regimes (Taylor 1998). Duvall (2004) specifically investigated the modifying influences of the sea breeze circulation previously mentioned from August 01–31, 2003. Her work provided data to illustrate that offshore flow, cooling surface temperatures, and the presence of a marine layer weakened the strength of the Monterey Bay sea breeze. Foster (1996) best highlights the necessity to understand the Monterey Bay sea breeze as his study, for the summer days of 1993–1995, showed a sea breeze occurred 92% of the time (Taylor 1998). These studies highlight the consistent and persistent influence of the Monterey Bay sea breeze on the local flow pattern most of the time.

As explained above, the Monterey Bay synoptic scale flow significantly influences the respective sea breeze evolution. Estoque (1962) utilized a 5 ms^{-1} synoptic wind in a physical model to determine the resultant sea breeze response. An offshore wind only allowed the sea breeze front to penetrate 8 km inland vice 32 km inland with zero wind; however, the offshore flow concentrated the horizontal temperature gradient thus intensifying the sea breeze front (Arritt 1992). In contrast, an onshore flow allowed for further inland penetration of the sea breeze, but with weakened circulation. Additionally, a southerly synoptic flow impacts the sea breeze front similarly to the offshore case, but with further penetration whereas a northerly synoptic flow reacts as did the onshore case (Estoque 1962). Arritt (1992) further detailed the synoptic flow impact indicating opposing ambient winds as strong as 6 ms^{-1} (11.5–12 knots) restricted the sea breeze location to the coastline. Stronger ambient winds maintained the sea breeze offshore while weaker flow allowed the front to progress inland (Arritt 1992).

Specifically, offshore ambient winds result in a shallower, later-developing sea breeze with less inland penetration (Gahmberg et al. 2009). Gahmberg et al. (2009) provided additional detail to the synoptic flow through the Coriolis effect. All directions are as seen from the sea with ambient flows left of the offshore direction providing the strongest opposing winds as Coriolis effects provide additional support in the offshore direction (Gahmberg et al. 2009). A geostrophic wind from 0 to 100° right of the offshore direction and lighter than 7 ms^{-1}, inhibits the sea breeze while also creating calm zones, which are not an emphasis of this particular study (Gahmberg et al. 2009). Geostrophic winds from 0 to 60° right from the offshore direction at 10 m s-1 are strong enough to inhibit the sea breeze, maintaining it off the coast (Gahmberg et al. 2009). Their previous research was all conducted in the absence of topography using idealized coastal geometry. These studies depict the impacts of magnitude and direction of the synoptic flow on sea breeze development although how they apply to the complex topography of the Monterey Bay region is not clear.

Static stability variations have also been shown to influence the evolution of sea breeze circulations. Estoque (1962) illustrated this through comparing a case with zero geostrophic wind as well zero geostrophic wind accompanied with an isothermal layer. The additional presence of an isothermal layer (strong static stability) inhibited sea breeze intensity as well as decreased sea breeze vertical structure (Estoque 1962). Arritt (1993) solidified Estoque’s (1962) conclusions utilizing the linear solution examining the horizontal and vertical wind components. In doing so, Arritt (1993) concluded strong static stability, specifically over the water, subdues both components with the stronger impact to the vertical than horizontal. Therefore, both Estoque (1962) and Arritt (1993) discovered strong static stability led to a less intense sea breeze.

D. THESIS OBJECTIVES

While many studies have been conducted on the general nature and development of the sea breeze, the multitude of parameters that can alter its development evolve differently due to geographically specific phenomenon. Specifically, the Monterey Bay area possesses a year-round consistent sea breeze generally occurring around the same

time during the day. The previous work conducted by Round (1993), Knapp (1994), and Duvall (2004) has addressed the general synoptic scale and local area effects of the Monterey Bay sea breeze and, in addition, Taylor (1998) addressed how these effects negatively impacted the Salinas Valley during a prescribed burn of Fort Ord on August 25, 1997. However, the specific combinations of flow details that delay sea breeze penetration into Fort Ord are not well known. October 24, 2003, provided another example of the difficulty in forecasting a delayed sea breeze onset as a Fort Ord prescribed burn transported smoke at low levels into Seaside, Monterey, Carmel, and Pacific Grove (Bakan 2004).

This study builds upon the above mentioned work and focuses on the following:

- To identify the background synoptic scale and delayed mesoscale flow response that occurs within a 24-hr "window" of a prescribed burn operation that indicate a delayed onset of the Monterey Bay area sea breeze.
- To characterize the primary sensitivities that may prevent a delayed sea breeze start-up.
- To develop "rules of thumb" to increase forecaster accuracy to better and more accurately predict late sea breeze start-up to support the operator.

This information will be essential to improve the support of the Joint U.S. Army and EPA endeavor of utilizing prescribed burns in order to safely and effectively remove ordnance from Fort Ord for further land development and conservation.

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III. DATA AND METHODOLOGY

This chapter details the data and methodology utilized in order to extract specific prescribed burn weather parameters from the North American Model (NAM) as well as the Climate Forecast System Reanalysis (CFSR) to further understand the synoptic and mesoscale weather patterns. Local area profiler data were used to select case studies while the models and cross sections further detailed the behavior of the sea breeze front into Fort Ord.

A. DATA ACQUISITION AND STRUCTURE

To characterize the synoptic scale patterns, the CFSR model was utilized. The CFSR is a global high-resolution model used to generate a best-estimate record of the ocean-atmosphere interaction. This reanalysis model provides approximately 38km (T382) resolution with 64 levels over a 31 year period from 1979 to 2009. This data is assimilated from historical and operational archives of observations providing a host of available parameters (Saha and Coauthors 2010). The Climate Forecast System version 2 (CFSv2) along with the CFSR continues data from 2009 to the present to provide the necessary data in support of this research for the time frame covering 2013 and 2014 (Saha and Coauthors 2014).

In order for the CFSR data to be in a usable structure for the purposes of this research, various steps occurred. First, the latitude/longitude grid of the CFSR data was interpolated to a 25 km grid on a Lambert conformal map projection (Nuss 2015). These interpolated fields of sea-level pressure, temperature, surface temperature, geopotential height, u wind component, v wind component, and surface pressure at six-hour intervals were used to diagnose the synoptic scale flow patterns (Nuss 2015). The interpolated fields can also be used for diagnostic calculations.

VISUAL developed by Nuss and Drake (1995) is a diagnostic and display program utilizing the National Center for Atmospheric Research (NCAR) graphics and Graphical Kernel System (GKS) primitives allowing the user to manipulate and produce numerous plots for various specified parameters (Nuss and Drake, 1995). Specifically, for

the CFSR data supporting the synoptic flow, a VISUAL script was written displaying geopotential height, wind speed, and wind direction at 850 mb on a horizontal sub grid producing a postscript image used to analyze the synoptic scale background flow.

To characterize the mesoscale patterns, the NAM model was utilized along with local observations to create a 1.25 km resolution local analysis. This analysis is referred to as the “mbay-anal.” The NAM is an operational model run by the National Centers for Environmental Prediction (NCEP) providing multiple domains in support of numerous weather parameters across the Continental United States (CONUS) (NOAA 2015). This study employed the 12km resolution NAM as it provides an accurate representation of the mesoscale environment inside the 48-hour window (NOAA 2015). The NAM forecasts served as the first guess in a multiquadric (MQ) based data assimilation system. The MQ analysis blended the NAM 12 km data with available local observations to produce hourly 1.25 km resolution analysis of the flow over the Monterey Bay Area. The MQ analysis system has been described for its two dimensional application by Nuss and Titley (1994). For this study a three dimensional version was used.

As with the CFSR data, the mbay-anal. data was plotted using VISUAL to depict the local flow patterns on an hourly basis. The mesoscale flow was characterized by displaying temperature, wind speed, and wind direction on a subdomain in grid coordinates with the observations overlaid. In order to further describe the sea breeze front onset, VISUAL provides the capability for cross-section plots (Nuss and Drake 1995). As a result, the potential temperature and cross sectional wind direction and magnitude within designated latitude and longitude endpoints were generated to show the circulations in the vertical.

B. METHODOLOGY

The purpose of this paper is to highlight patterns in the synoptic scale and relate them to the local area environment in order to enhance forecast accuracy inside the 24 hour window prior to a prescribed burn operation. First, archived profiler data was examined to classify a potential “burn day(s).” As such, this is not an exhaustive study of sea breeze evolution under varying synoptic patterns but instead is on sea breeze

variation under a fairly consistent large-scale flow pattern. Once completed, each respective day was then analyzed by employing the CFSR and mbay-anal. models to depict the environment. In addition, cross sections were further used to illustrate the nature of the sea breeze front as it progressed through the Monterey Bay into Fort Ord.

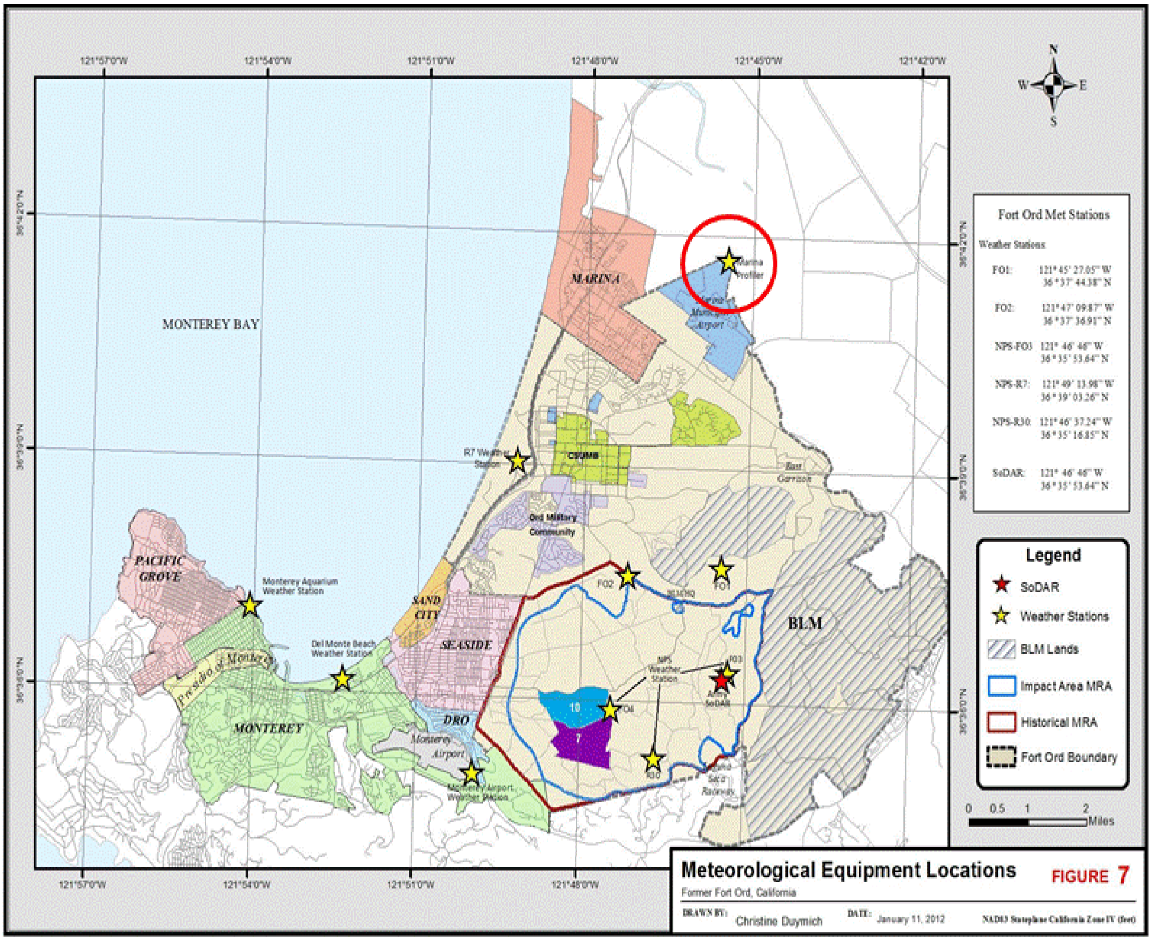
1. NPS Profiler at Fort Ord

The mixing height and surface wind direction are the first two basic ingredients necessary to support a potential prescribed burn operation. Therefore, the NPS profiler at Fort Ord offers an archived database from 1994 to the present depicting these parameters on an hour versus altitude plot. The 915 MHz Doppler wind profiler, located at Marina Municipal Airport (36.69°N latitude, 121.76°W longitude), plots mixing height using surface virtual temperature as well as wind speed and direction from the surface to 5,000 feet above sea level (Figure 6 for profiler location; Gahard 2003). In addition, the profiler site provides an hourly depiction of the surface meteorology to include wind speed, wind direction, temperature/dew point, sea level pressure, shortwave irradiance, and longwave irradiance. For the purposes of this research, the mixing height, surface wind direction, and surface wind speed were the only parameters necessary to select potential burn days.

The calendar year window for burn operations occurs from July through December with the months of September through November as the primary focal months. Therefore, those focal months were the baseline of this study for the years of 2013 and 2014. As delineated in Duymich et al. (2015) the target mixing height is above 1,500 feet to support appropriate smoke behavior. Additionally, the prescribed burn is only feasible with a delayed sea breeze onset occurring between 2000 UTC–2300 UTC vice the climatological 1700 UTC–1900 UTC onset. In analyzing the profiler data, a potential case study day was determined if the mixing height was greater than 1,500 feet beginning approximately 1600 UTC–1700 UTC and remaining until the sea breeze front had moved into the area and denoted by the hatched region on the profiler (Figure 7). Specifically, on October 4, 2013, the profiler data illustrated these criteria and was further supported by the surface meteorology from the profiler with the wind direction shifting from easterly to westerly at approximately 2200 UTC (Figure 8). Conducting this analysis from

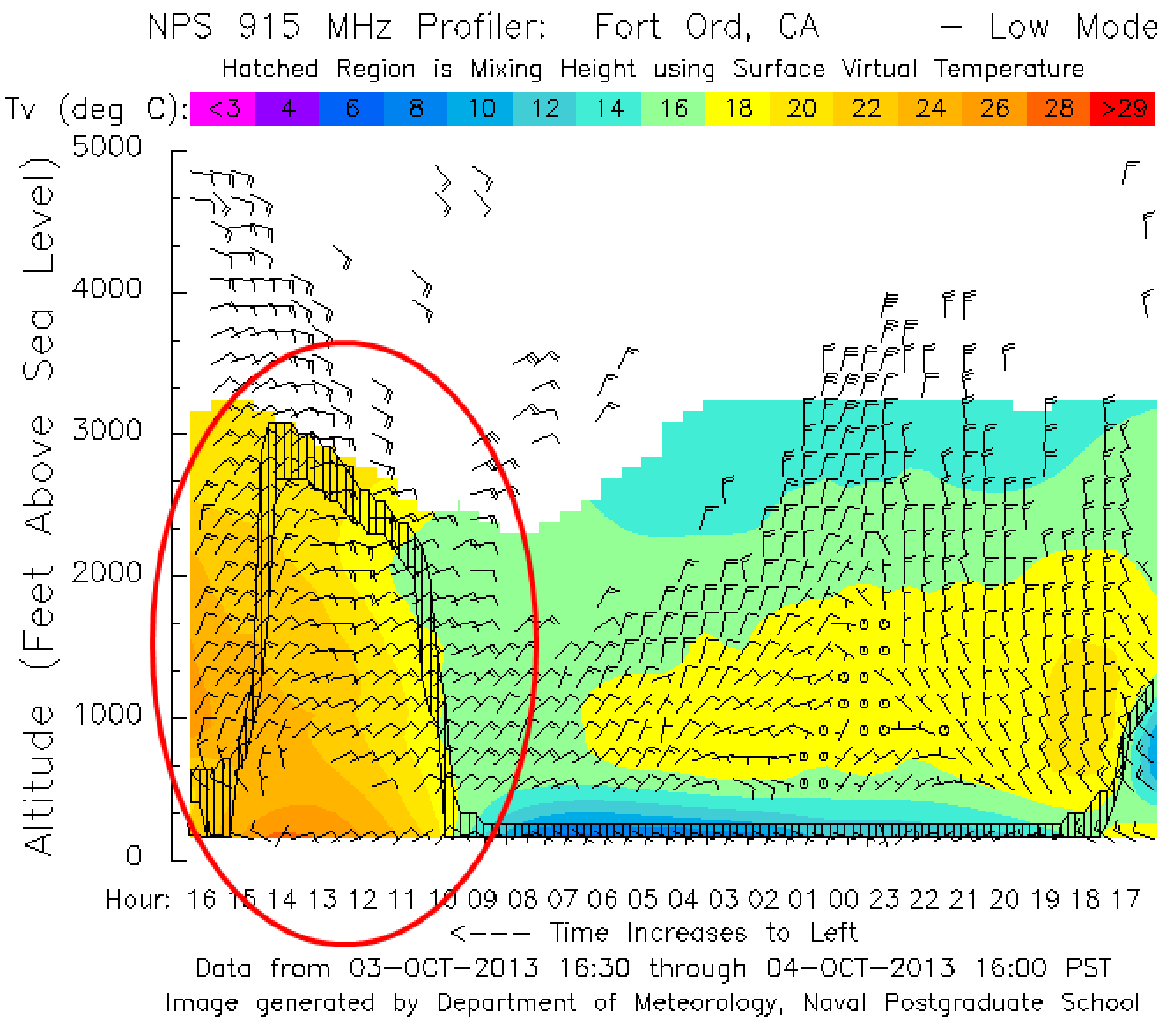
September through November for 2013 and 2014 (182 days) resulted in 12 potential case studies (6.6%) supporting the necessary initial parameter guidelines for a prescribed burn.

Figure 6. Fort Ord aerial map



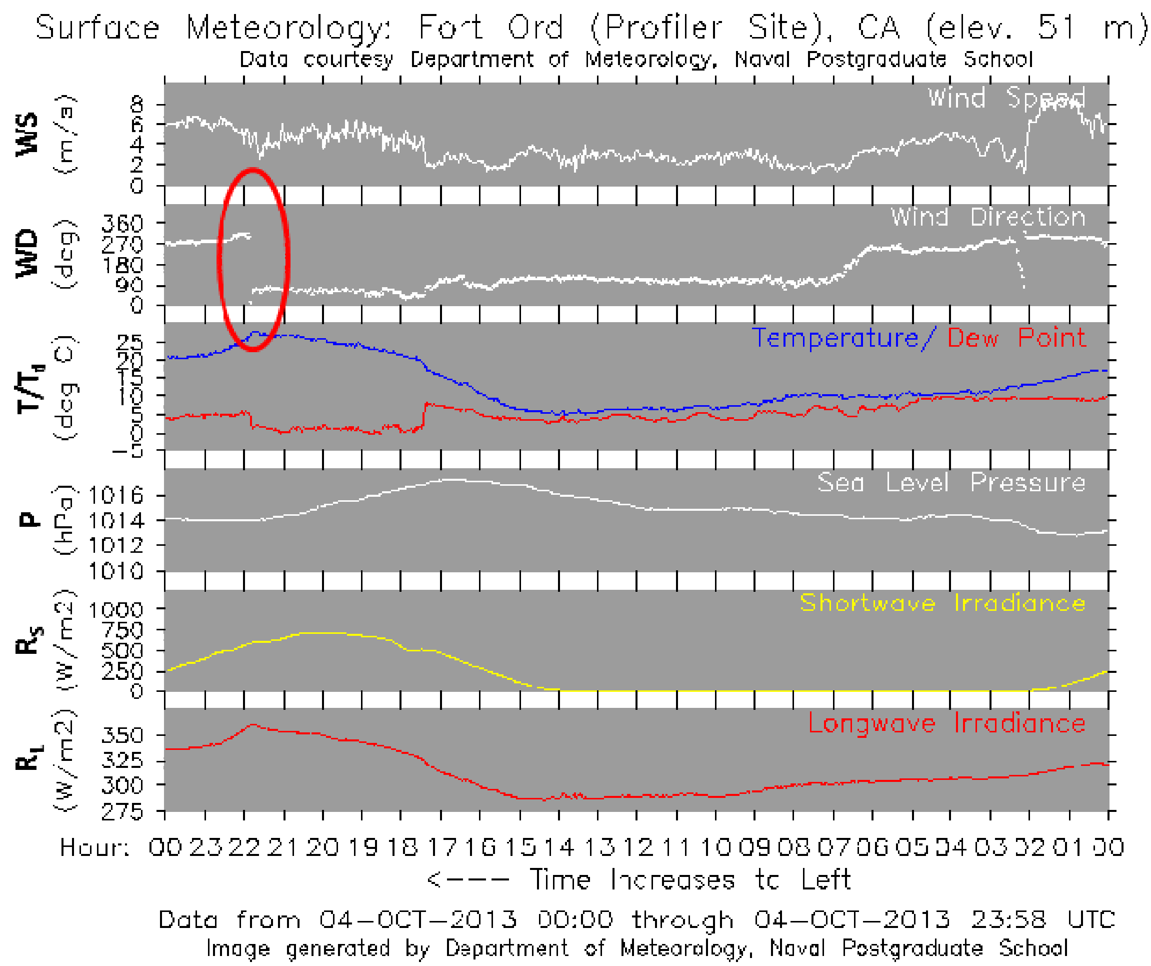
NPS Profiler at Fort Ord (denoted by the star within the red circle) located at the Marina Municipal Airport. Source: Duymich, C., 2012: Fort Ord Prescribed Burn Program 2012. Accessed 20 October 2015.

Figure 7. Wind and virtual temperature measurements by the NPS Profiler at Fort Ord on October 4, 2013



Data depicting >1,500 feet mixing height through the time period of interest along with delayed onshore winds. Source: Monterey Area Environment, 2015: NPS 915MHz profiler at Fort Ord mixing height: 2003. Accessed 06 April 2015

Figure 8. NPS surface measurements at Fort Ord for October 4, 2013



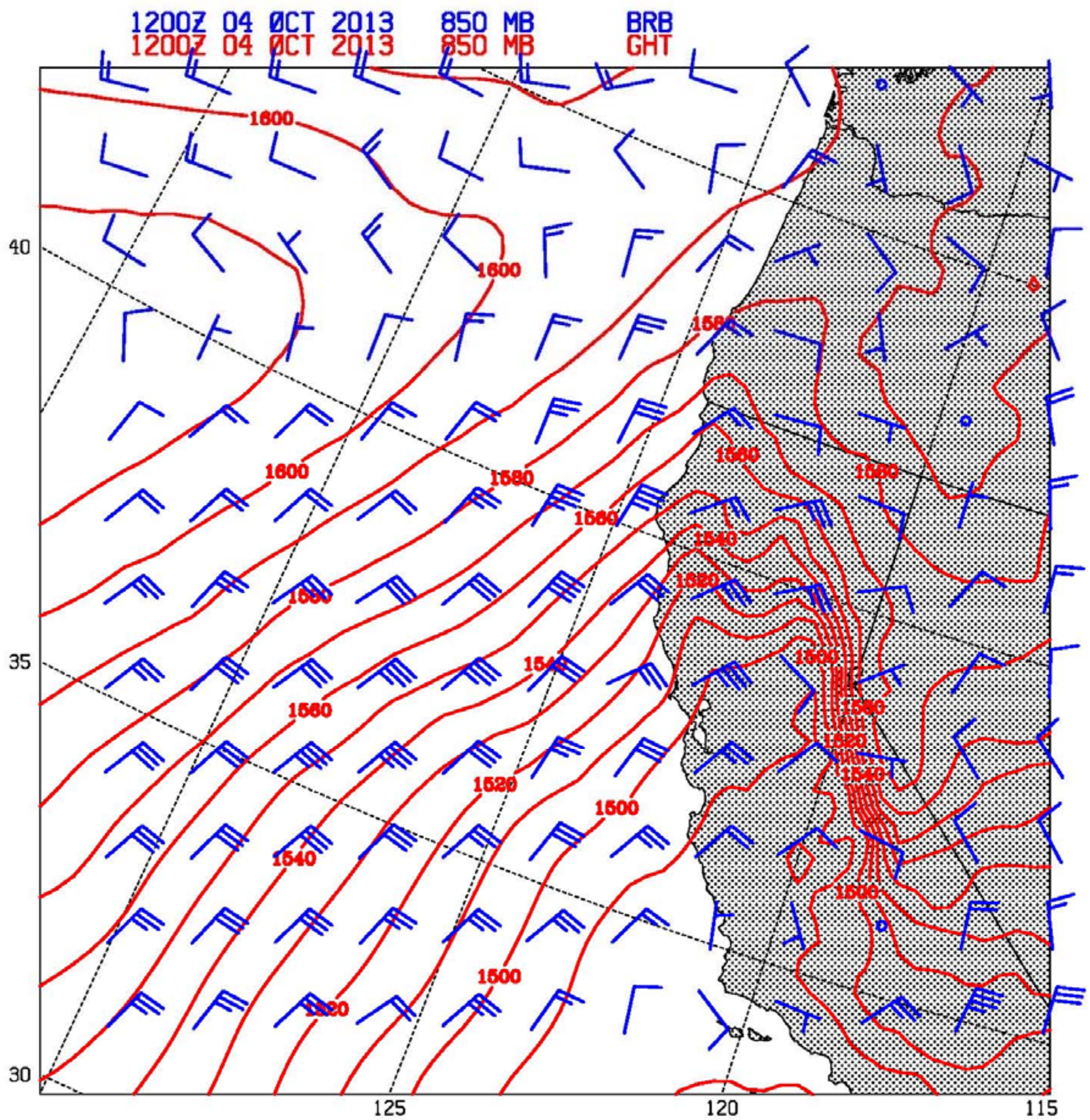
Data depicting onshore flow occurring approximately 2200 UTC. Source: Monterey Area Environment, 2015: NPS meteorological station at Fort Ord wind profiler site: 2003. Accessed 06 April 2015

2. CFSR Synoptic Pattern

With the respective potential prescribed burn days decided upon, the next step in the process was to better understand the synoptic flow pattern(s) to expose their effect(s), if any, on the localized sea breeze front evolution. To do so, the 850 mb geopotential heights as well as the 850 mb wind speed and directions were plotted (see Figure 9) to characterize the respective dominant and supporting pressure system(s) in the region. These fields were plotted every six hours (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC) beginning 12 hours before the respective day of interest and running 36 hours

through the day of interest. For example, when analyzing October 4, 2013, the CFSR data fields were generated from 1200 UTC on October 3, 2013, to 0000 UTC on October 5, 2013, every 6 hours. Therefore, this provided the necessary data to understand the synoptic structure prior to and during the timeframe of a prescribed burn.

Figure 9. CFSR data for 1200 UTC on October 4, 2013



850 mb geopotential height are depicted with red contours lines. 850 mb wind barbs are depicted in blue.

From the synoptic perspective, the presumption was that all case studies selected for further analysis should depict a synoptic scale flow supportive of offshore flow that delayed the sea breeze front. As depicted in Figure 9, a high pressure system resides off the northern coast of California. This structure supports anticyclonic flow around the high bringing northeasterly winds into the Monterey Bay area. Additionally, strong winds (25–35 knots) resulting from a tight geopotential height gradient along the coast also supports the initial reasoning of a delayed sea breeze onset. Northeasterly to southeasterly flow through the east in the synoptic scale was desired to enhance the localized offshore wind component which, in turn, works contrary to onshore sea breeze flow.

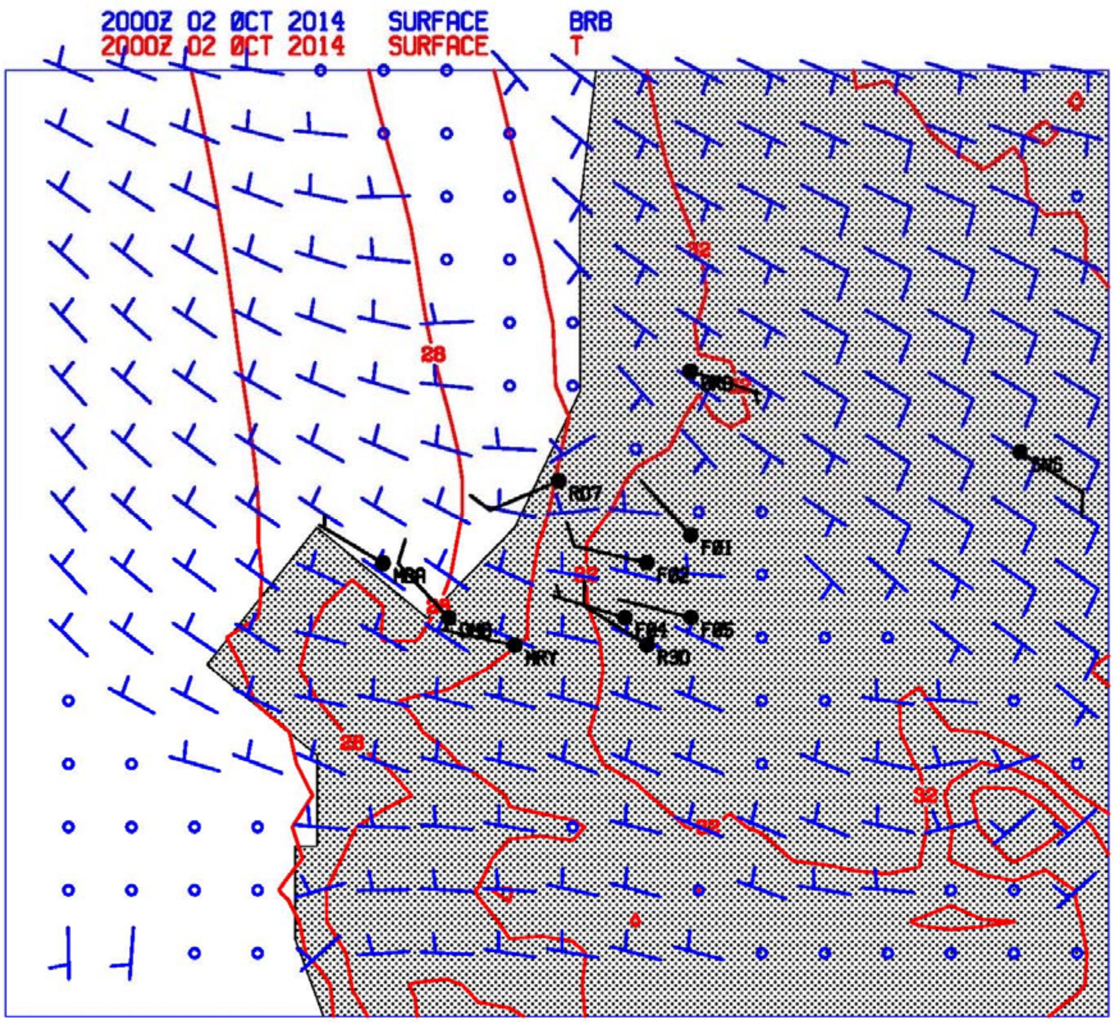
3. Monterey Bay Local Area Pattern

The characterization of a favorable synoptic scale flow pattern leads into further investigation of the Monterey Bay area to understand the local response. To illustrate the local response, the surface level temperature contours, wind direction, and wind speed were plotted with the local area observations included (Figure 10). The local area observations provided additional verification to validate the analyzed wind field. The mbay-anal was run every hour from 1200 UTC to 2300 UTC for all potential prescribed burn days of interest. Additionally, the surface temperature contours depicted the meridional gradient (cross-shore) in order to investigate its potential influence on the sea breeze evolution.

As illustrated below, the wind direction depicts the location of the sea breeze front at the respective time based on a shift in wind direction from onshore to coast parallel or offshore. The observations also validate the direction and magnitude of the mbay-anal winds. This local structure illustrates the sea breeze front has progressed into the Fort Ord area for the day and time shown in Figure 10. Of note in this case, the wind speed and direction is light and southeasterly at the NPS profiler location, utilized to initially determine case studies, while westerly winds are evident in the Fort Ord area. Thus, strictly utilizing the NPS profiler would have provided an incorrect assessment of the sea breeze onset. Therefore, this example illustrates the potential topographic effects that further complicate the dynamics to correctly forecast prescribed burn weather parameters

and requires further analysis to understand the relationship between the synoptic and mesoscale features.

Figure 10. NAM 12 km data for 2000 UTC on October 2, 2014



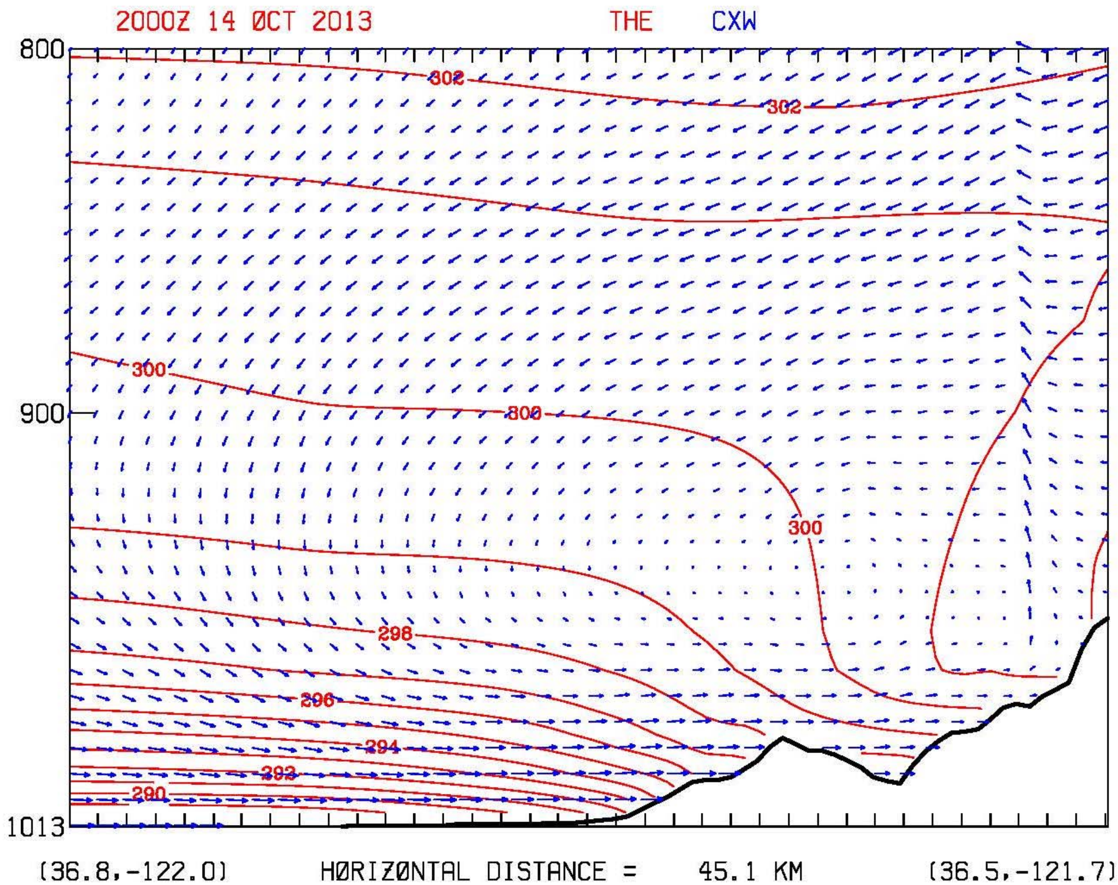
Surface temperature contours are depicted in red, wind barbs in blue, and observations in black.

4. Mbay-anal. Local Area Cross Section

To enhance the ability to characterize the sea breeze front, the mbay-anal was visualized through a cross section. The cross section was taken from the middle of the Monterey Bay (36.8, -122.0) through Fort Ord and into the Salinas Valley (36.5, -121.7)

covering a horizontal distance of 45.1 km. The cross sections were produced hourly from 1600 UTC to 2300 UTC for each respective case study. This selected timeframe covered the pre- and post-sea breeze front evolution. Potential temperature as well as wind direction and magnitude in the direction of the cross section are plotted from the surface to 800 mb (Figure 11). Plotting the wind direction and magnitude best locates the sea breeze front where an onshore to offshore shift occurs. The respective synoptic flow is evident above the 900 mb level and the potential temperature provides the vertical thermodynamic structure that drives the sea breeze. As a result, these parameters best illustrate the location and structure to either support or resist the sea breeze front evolution.

Figure 11. NAM 12 km cross section for October 14, 2013



Potential temperature contours are depicted in red. Wind direction and magnitude in direction of cross section are depicted in blue.

After examining the occurrence of the sea breeze onset timing through the mbay-anal mesoscale analysis, the next step was to diagnose the potential connection between the synoptic and mesoscale circulations illustrated in the cross section. In reference to Figure 11, the cross section at 2000 UTC on October 14, 2013 can be characterized as a textbook example of the localized sea breeze. The potential temperature structure represents high pressure over the Monterey Bay region detailed by a tight vertical potential temperature gradient over the cooler air near the surface over the water. In contrast, low pressure is located inland as evident from the warmer temperature in the column over the land. The cross-sectional winds clearly show a sea breeze structure with low-level onshore flow progressing inland towards the thermal low. Conversely, winds inland ascend over the localized low pressure with offshore return (seaward) flow in the 900 mb to 800 mb layer. Thus, the sea breeze onset has already occurred and has progressed into the Fort Ord region. This methodology was employed to all case studies for sea breeze characterization to obtain time and depth of the sea breeze flow.

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IV. ANALYSIS AND RESULTS

The 12 case studies which met the basic pattern out of a possible 182 days were examined to determine potential patterns connecting the synoptic scale wind field to its corresponding effect on the diurnal mesoscale flow thus delaying the local sea breeze response over Fort Ord. The 12 cases were characterized by their synoptic scale flow direction, their thermal gradient across the coast, and their background static stability. Each case was slightly different but some cases had considerable similarity and will not be presented. The primary factor in all cases was the time when the sea breeze impacted Fort Ord. When this time was later than the typical 1000 PST–1100 PST onset, the three possible contributing factors were examined in detail. The cases are presented based on the most significant contributing factor. These eight cases illustrate patterns that were categorized into the following three flow patterns: synoptic flow influence, static stability influence, and temperature gradient influence.

A. SYNOPTIC FLOW INFLUENCE

Nine of the 12 cases appear to have a delayed sea breeze onset due to the influence of synoptic scale flow. Of these nine cases, five are detailed below as the other four cases displayed similar results. Wexler (1946), Estoque (1969), Arritt (1993), and Nuss (2003) all acknowledge the importance of the synoptic flow intensity and direction resulting in different sea breeze dynamics. Thus the most likely trigger for a delayed sea breeze onset is due to synoptic flow. This author is unaware of these concepts applied to the Monterey Bay under the strict constraints posed by burning operations. The first case explains the effect of a weak southerly synoptic flow pattern. The second case rotates the synoptic flow slightly north to easterly. The third case shows the effect of changing synoptic flow during the period of interest. In all cases, sea breeze onset was delayed until about 1900 UTC–2000 UTC. Lastly, the fourth and fifth cases both contain northeasterly-northerly flow but varying in strength with Case #5 stronger than Case #4.

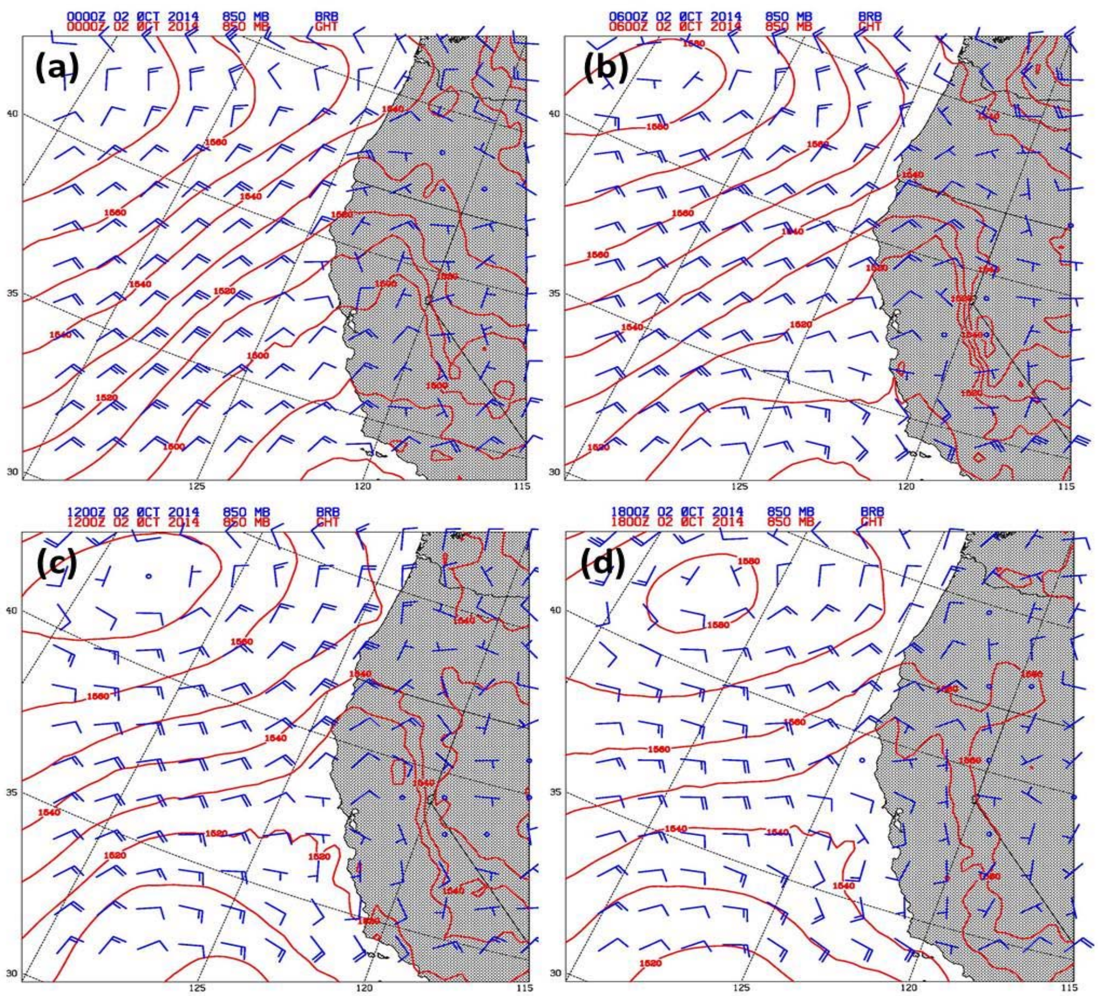
1. October 02, 2014–Weak Southerly Flow

October 02, 2014, shows a synoptic scale pattern of high pressure located off the Northern California coast and low pressure off the Southern California coast (Figure 12). From 1200 UTC (Figure 12c) to 1800 UTC (Figure 12d) the high pressure system weakens with the low pressure shifting further north. As a result, the 1200 UTC and 1800 UTC analysis illustrate light (~10 knots) southerly winds over the Monterey Bay region. While the synoptic flow is not directly oriented to oppose the sea breeze circulation, it is still enough to provide an opposing component to act as a blocking mechanism to sea breeze development. Figure 13a shows the mesoscale analysis at 1600 UTC that illustrates a southerly-southeasterly flow over the area south of the Monterey Bay in direct opposition of the sea breeze. This opposing flow prolongs the diurnal land breeze. Strong offshore flow is also seen from the surface to 900 mb in the 1600 UTC cross section in Figure 14a. The 1900 UTC analysis (Figure 13d) shows an increased cross coast temperature gradient along with the sea breeze beginning to overwhelm the synoptic flow. Additionally, the cross section at 1900 UTC (Figure 14b) illustrates heating over the land seen by the increase in potential temperature on the right side of the figure, which acts to increase the cross sectional thermal gradient. As a result, the surface flow now exhibits an onshore flow in direct opposition to the synoptic flow. Observations over Fort Ord shown in Figure 15a indicate onshore flow at 2000 UTC over the Fort Ord area while southeasterly flow continues in the Salinas Valley. The sea breeze progresses into Fort Ord around 2000 UTC (Figure 15a) with a classical sea breeze structure of onshore flow at the surface to 950 mb, vertical flow east of Fort Ord, and return flow offshore above 900 mb illustrated by the cross section in Figure 15b. Consequently, due to the Monterey Bay orientation, southerly synoptic flow provides the opposing flow necessary to delay the sea breeze response and provide a larger window for prescribed burning operations.

The orientation of the Salinas Valley with respect to the synoptic scale flow in this case produced considerable local variations in the flow. The Salinas Valley is oriented in the southeast to northwest direction and therefore a south-southeasterly synoptic flow develops a funneling effect through the valley. This influence is best seen

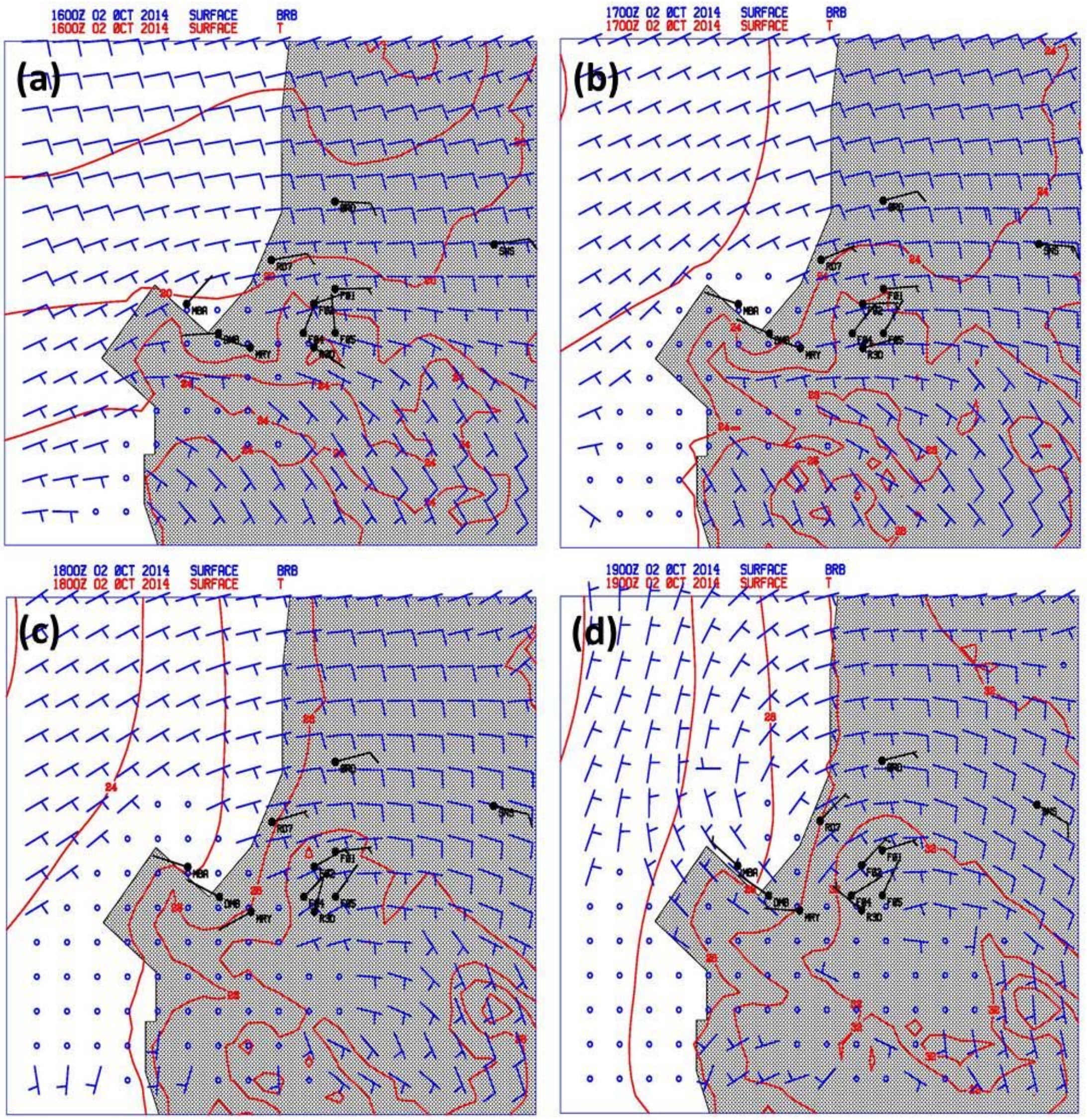
in the 1800 UTC (Figure 13c) and 1900 UTC (Figure 13d) analyses where the winds are oriented southeasterly through the Salinas Valley and are stronger (10 knots) than the respective observations at Fort Ord with weaker northeasterly winds (5 knots). This intensified wind flow through the valley continues to offset the diurnal effects of the sea breeze, while the weaker easterly flow over the Monterey Bay has already turned onshore consistent with the diurnal sea breeze flow. Additionally, Figure 13c and 13d shows a distinct front or wind shift line oriented parallel to the coast through the Fort Ord area. This is important to note as the NPS Profiler at 2000 UTC (not shown) does not provide evidence of the sea breeze onset or inland penetration that is clearly evident in the Fort Ord observations. Thus relying strictly on the NPS Profiler provides an inaccurate picture on the true environment over the burn operation's area of interest. This case clearly shows how the unique topographic features of the Monterey area add to the complexity of the flow evolution due to the sea breeze.

Figure 12. 850 mb geopotential height and winds



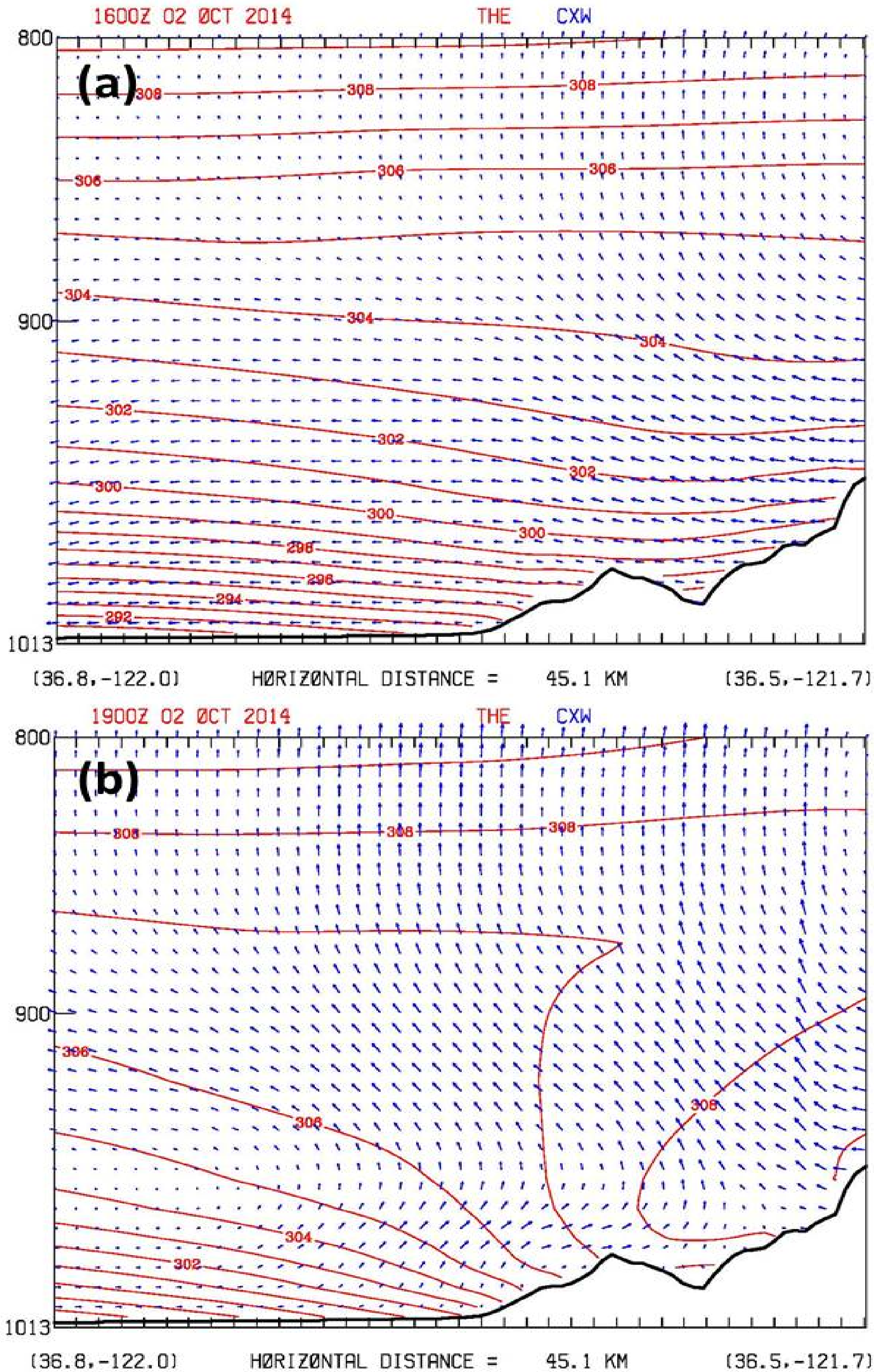
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 02 October 2014

Figure 13. Surface temperature and winds



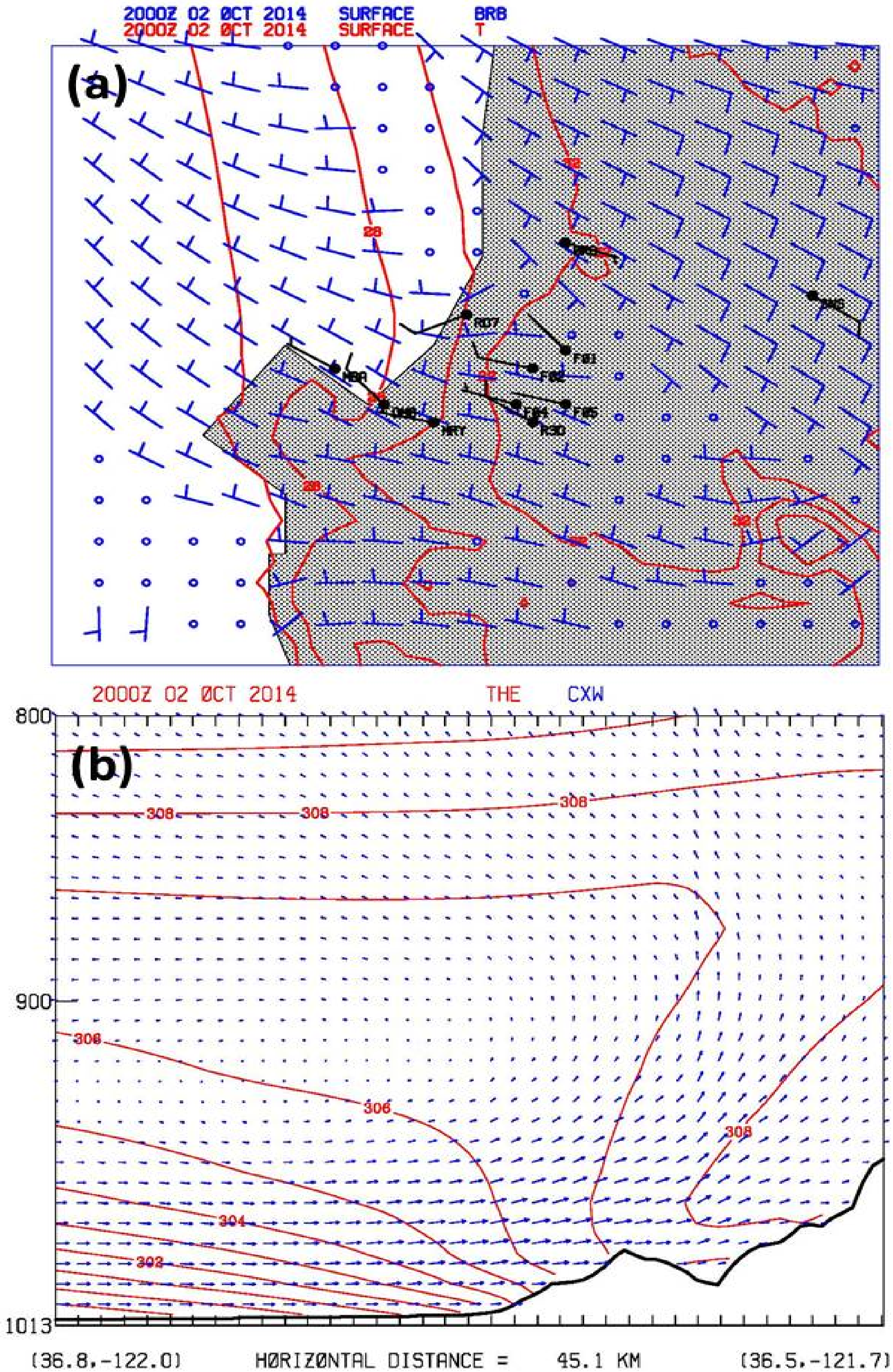
1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 02 October 2014

Figure 14. Potential temperature and winds in the plain of the cross section



1600 (a) and 1900 (b) UTC 02 October 2014

Figure 15. Surface and cross section plots



Surface temperature and winds (a) and potential temperature and winds in the plain of the cross section (b) at 2000 UTC 02 October 2014

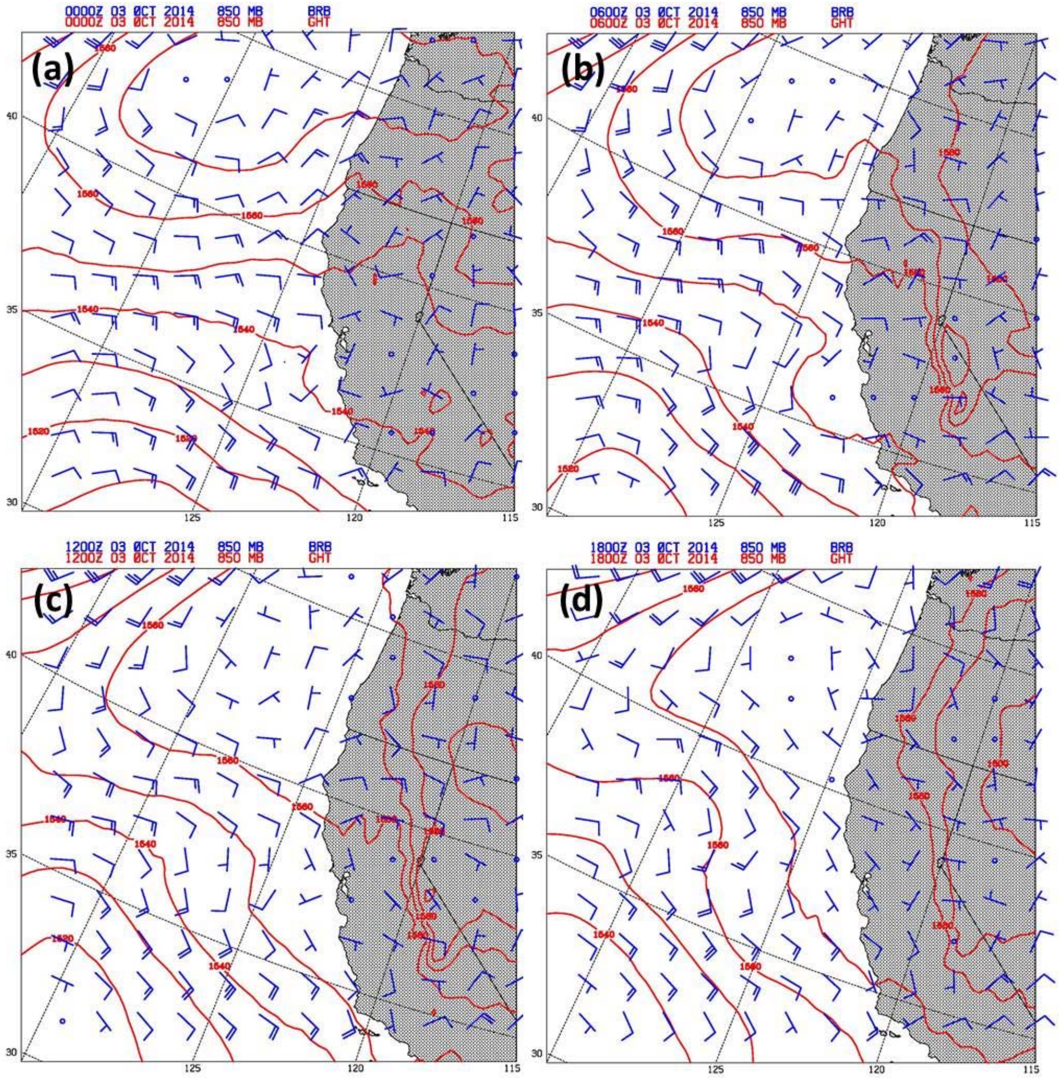
2. October 03, 2014–Weak Southeasterly Flow

The October 03, 2014, case presents some minor changes in the synoptic scale flow from the previous case study, but results in a similar delay in the sea breeze onset until 2100 UTC. Specifically, 1200 UTC (Figure 16c) and 1800 UTC (Figure 16d) depict weak 5–10 knots southeasterly flow into the Fort Ord region. While the synoptic flow is weaker than Case #1, the southeasterly synoptic flow direction directly counters the developing local sea breeze from a northwesterly direction. Figure 17a illustrates the synoptic flow response at 1600 UTC as the weak southeasterly synoptic flow results in weak southeasterly surface flow over the Fort Ord region. The cross section in Figure 19a also depicts offshore flow at 1600 UTC from the surface through the 800 mb levels. Of note, the cross section also shows sinking air from the 900 mb to 800 mb levels down to the surface over the ocean which is reflected in Figure 17a at 1600 UTC with stronger easterly winds over the Monterey Bay versus the calm/weak offshore flow observations over Fort Ord. As a result, the diurnal land breeze in tandem with the supporting synoptic flow holds back sea breeze development until after this time. Eventually, Figure 17d shows the winds beginning to shift northerly off the coast at 1900 UTC with calm variable winds observed at the coast depicting the interaction of the developing sea breeze with the opposing background winds. By 2000 UTC, Figure 18a depicts a distinct sea breeze front along the coast moving into Monterey but not advancing over Fort Ord until 2100 UTC as shown in Figure 18b. Figure 19b illustrates the sea breeze circulation at 2100 UTC with onshore flow at the surface vertically to 925 mb with the resulting upper level flow weakly offshore from 900 mb to 800 mb. Therefore, while the magnitude of the synoptic flow was weaker than on October 02, 2013, the direction of the ambient flow provides more direct opposition to the sea breeze resulting in the same impacts to the time of sea breeze onset.

As with the previous case, the direction of the synoptic flow once again is impacted by the orientation of the Salinas Valley, providing a funneling effect for the southeasterly winds. The decreased magnitude of the winds to 5 knots vice 10 knots lessened the effect but still produced an impact by maintaining southeasterly flow in the Salinas Valley even after the sea breeze started near Fort Ord. Areas of intensified wind

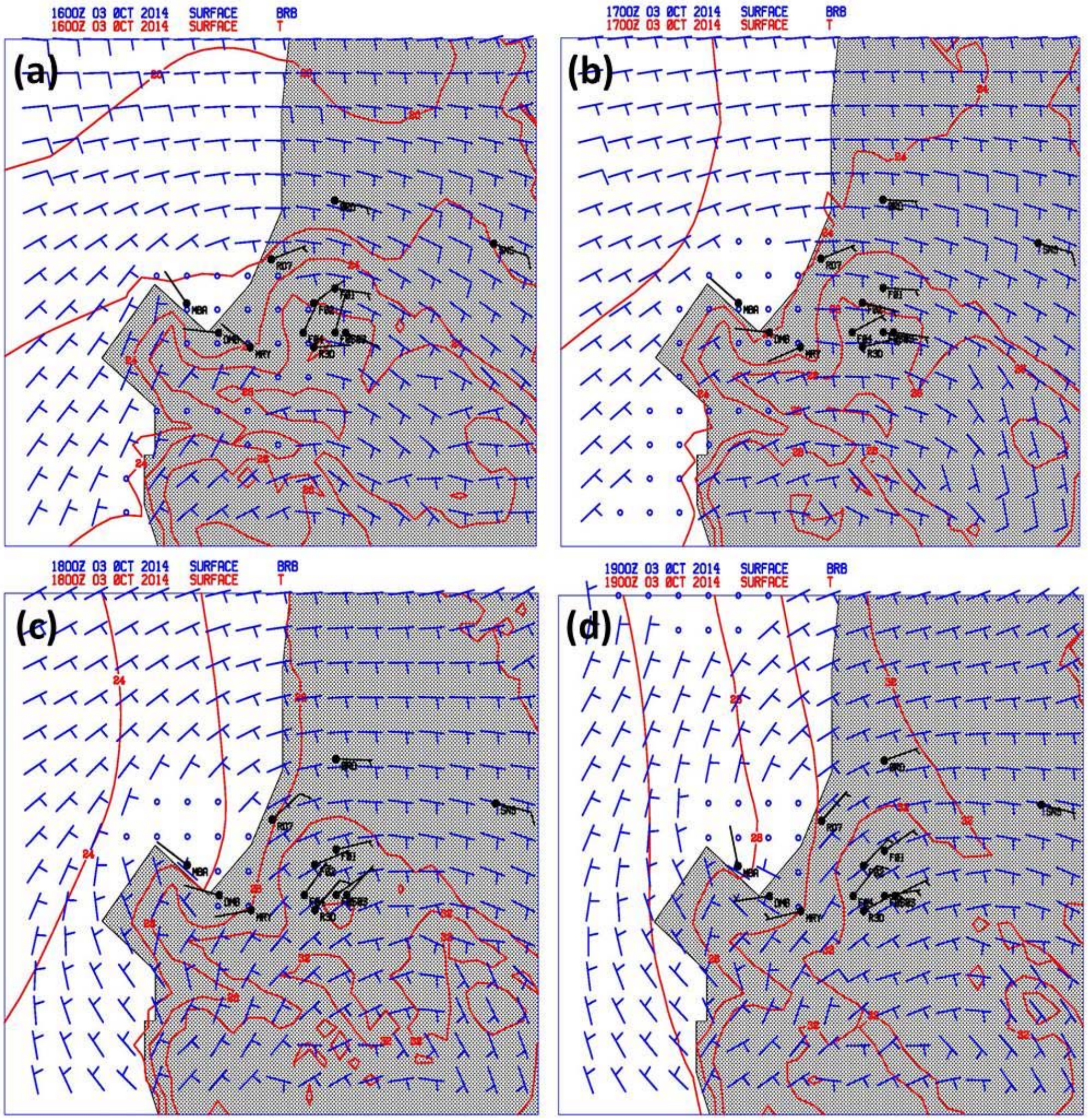
magnitude in the observations at 1600 UTC (Figure 17a) and 1700 UTC (Figure 17b) in the Salinas Valley show 10 knot flow vice the 5 knot flow over Fort Ort for the same time periods. While minor, Figure 18a depicts the resultant impacts as the sea breeze at 2000 UTC penetrates inland at Monterey but is restricted to the coastline in Marina due to the increased opposing flow from the Salinas valley. Although weak in magnitude, Figure 18b shows the sea breeze at 2100 UTC throughout the region eventually overwhelms the opposing flow allowing penetration inland. As a result, in this case the NPS Profiler did not have as much variation from the Fort Ord observations as they both experienced the sea breeze onset at approximately the same time. Therefore, the synoptic flow direction made up for the magnitude deficiency to delay sea breeze onset by about the same amount in the previous case.

Figure 16. 850 mb geopotential height and winds



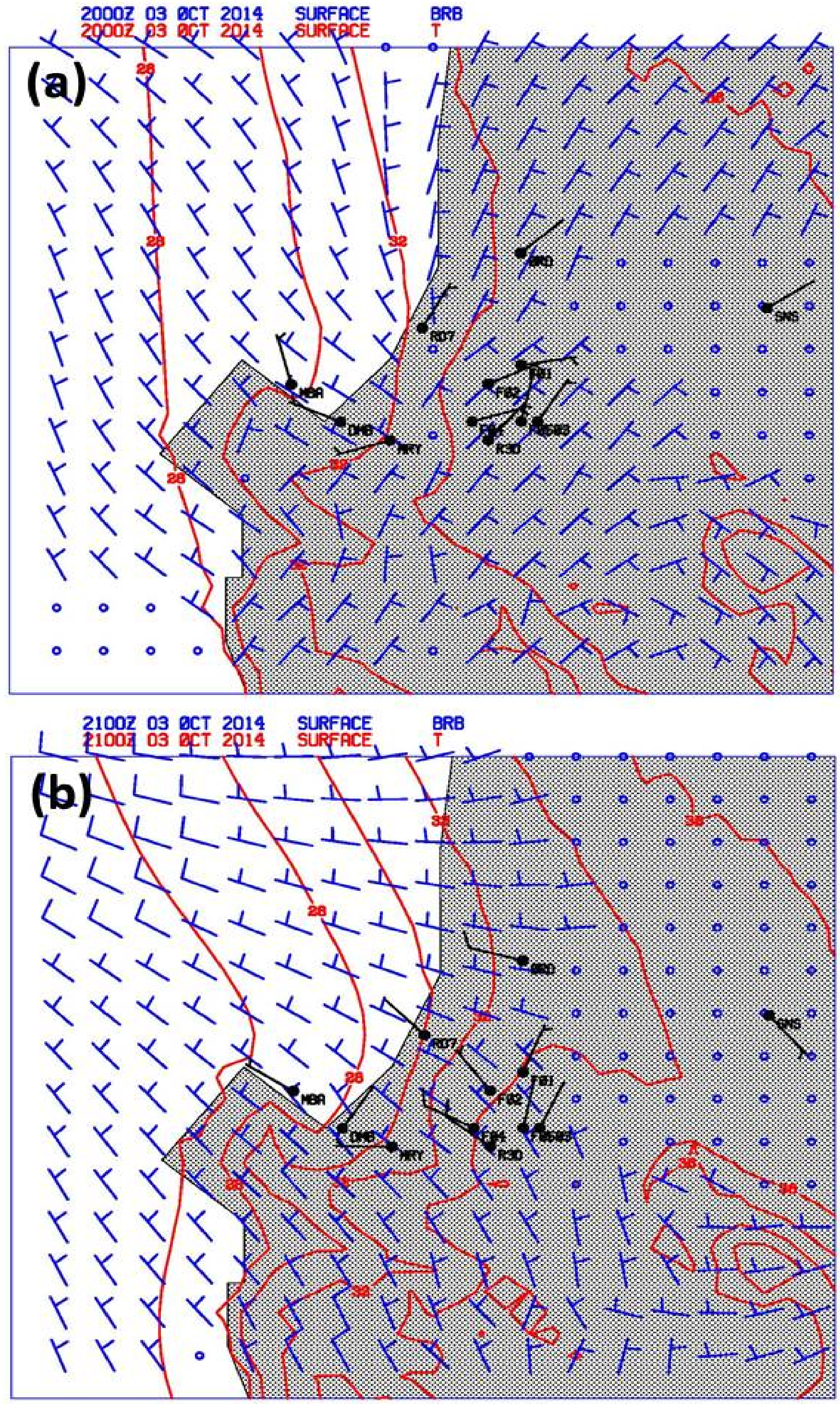
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 03 October 2014

Figure 17.   Surface temperature and winds



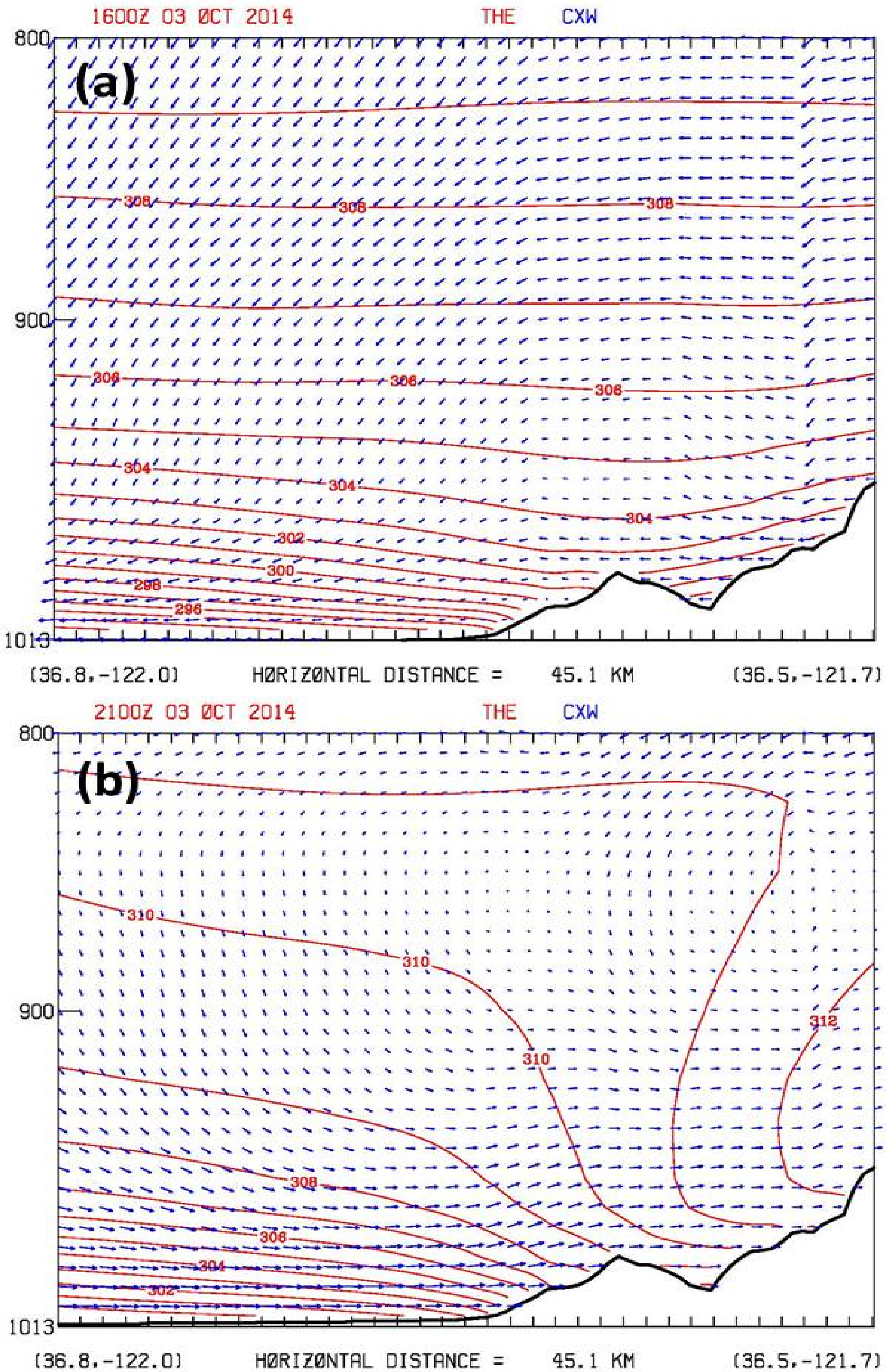
1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 03 October 2014

Figure 18. Surface temperature and winds



2000 (a) and 2100 (b) UTC 03 October 2014

Figure 19. Potential temperature and winds in the plain of the cross section



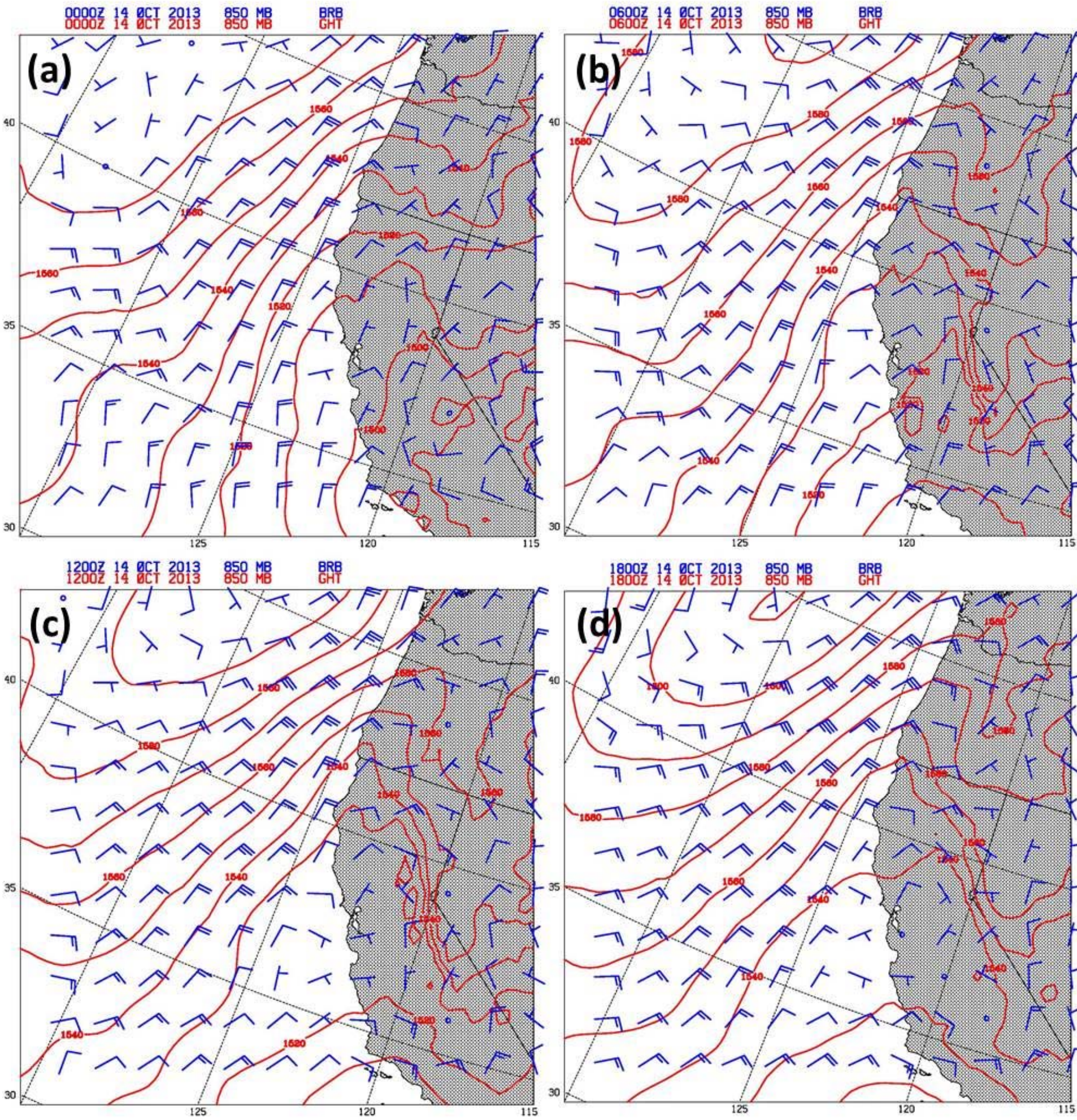
1600 (a) and 2100 (b) UTC 03 October 2013

3. October 14, 2013–Weak Easterly Flow

October 14, 2013, builds upon the previous two case studies by again displaying weak synoptic scale winds, but this time from an easterly direction which also delayed the sea breeze onset until 2000 UTC. Figure 20 shows northeasterly flow at 0600 UTC (Figure 20a) shifting to easterly flow by 1200 UTC (Figure 20c) over the Monterey Bay and staying easterly from 1200 UTC to 1800 UTC (Figure 20d). While easterly winds do not directly oppose the local sea breeze over Fort Ord, frictional turning from the Monterey Bay coastline shape turns the winds more southeasterly, producing a component in opposition to the sea breeze. Figure 22a at 1600 UTC illustrates this as the synoptic flow above 900 mb presents a strong offshore component that assists in maintaining the weak opposing component of the remnant land breeze at the surface. Figure 21 depicts the evolution of 5 knot easterly synoptic flow, which prevents the cyclonic turning of the winds in the Monterey Bay until 1800 UTC. At 1900 UTC, the cross-coast thermal gradient intensifies so that the sea breeze flow is beginning to match the ambient flow. Figure 22b shows the establishment of the sea breeze at 2000 UTC at the surface with a complete return circulation supported in the 900 mb to 800 mb layer.

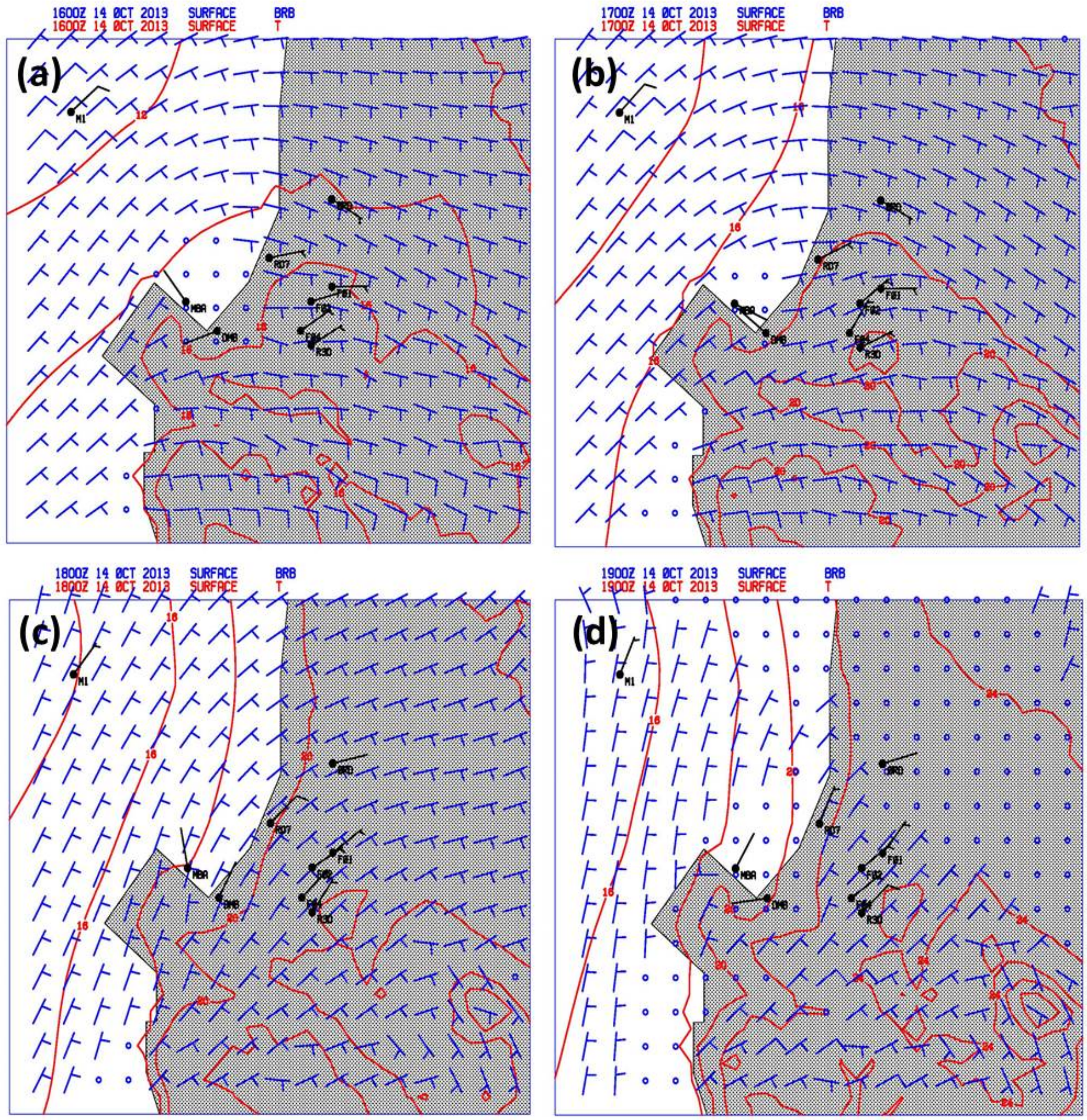
As seen in the previous two cases, a weak synoptic flow of 5–10 knots provides enough of an opposing component to the sea breeze to impact sea breeze onset timing. Specifically to this case, a 5 knot easterly synoptic flow pattern is strong enough to support the already established land breeze to resist the sea breeze (Arritt 1992) and delays the sea breeze onset long enough to conduct a prescribed burn before the sea breeze front proceeds inland (Estoque 1962). This scenario provides the necessary ingredients for prescribed burning operations presenting substantial mixing heights, weak synoptic flow that is beneficial in opposing the sea breeze, and, most importantly, a delayed sea breeze onset at Fort Ord.

Figure 20. 850 mb geopotential height and winds



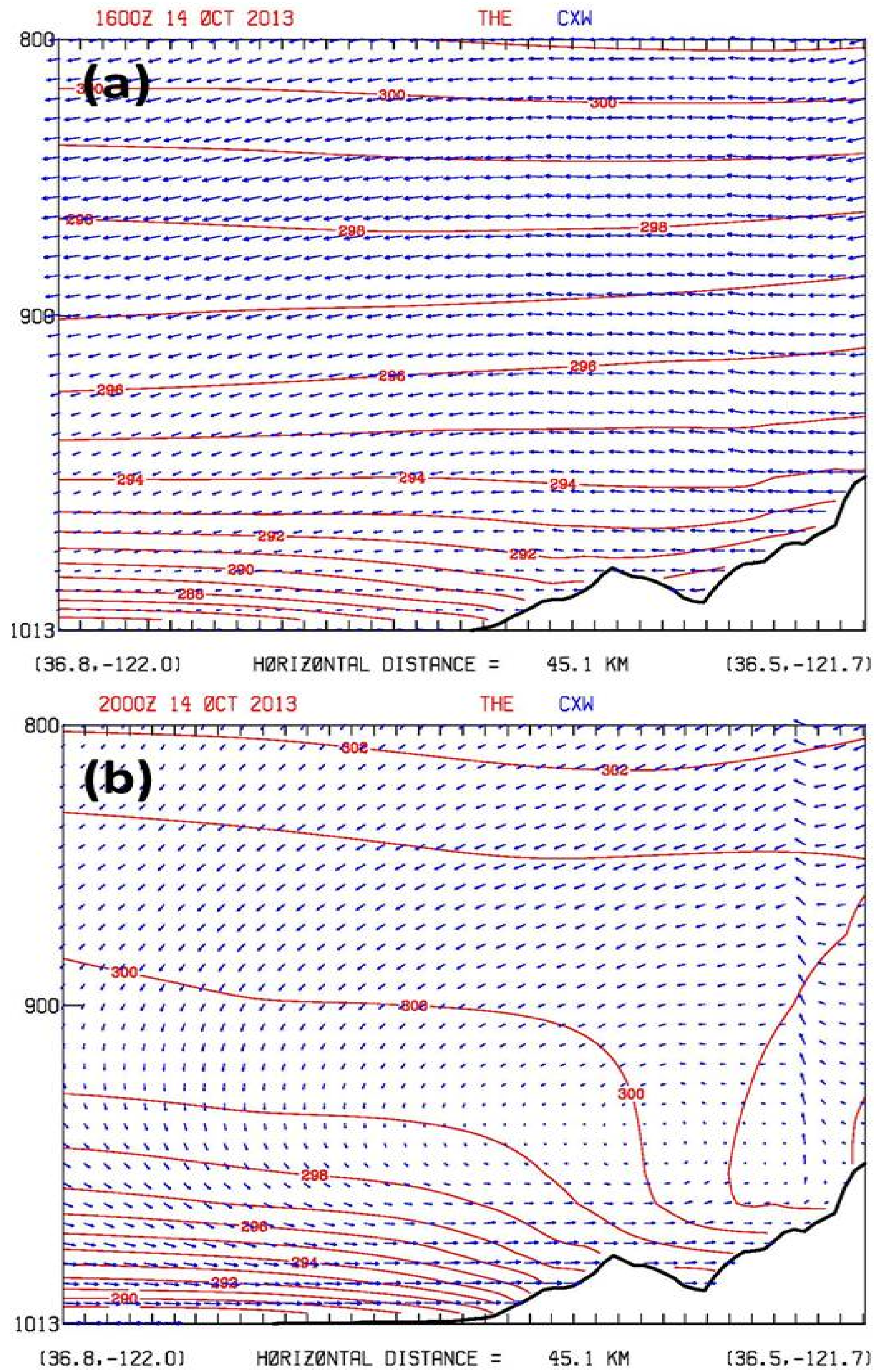
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 14 October 2013

Figure 21. Surface temperature and winds



1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 14 October 2013

Figure 22. Potential temperature and winds in the plain of the cross section

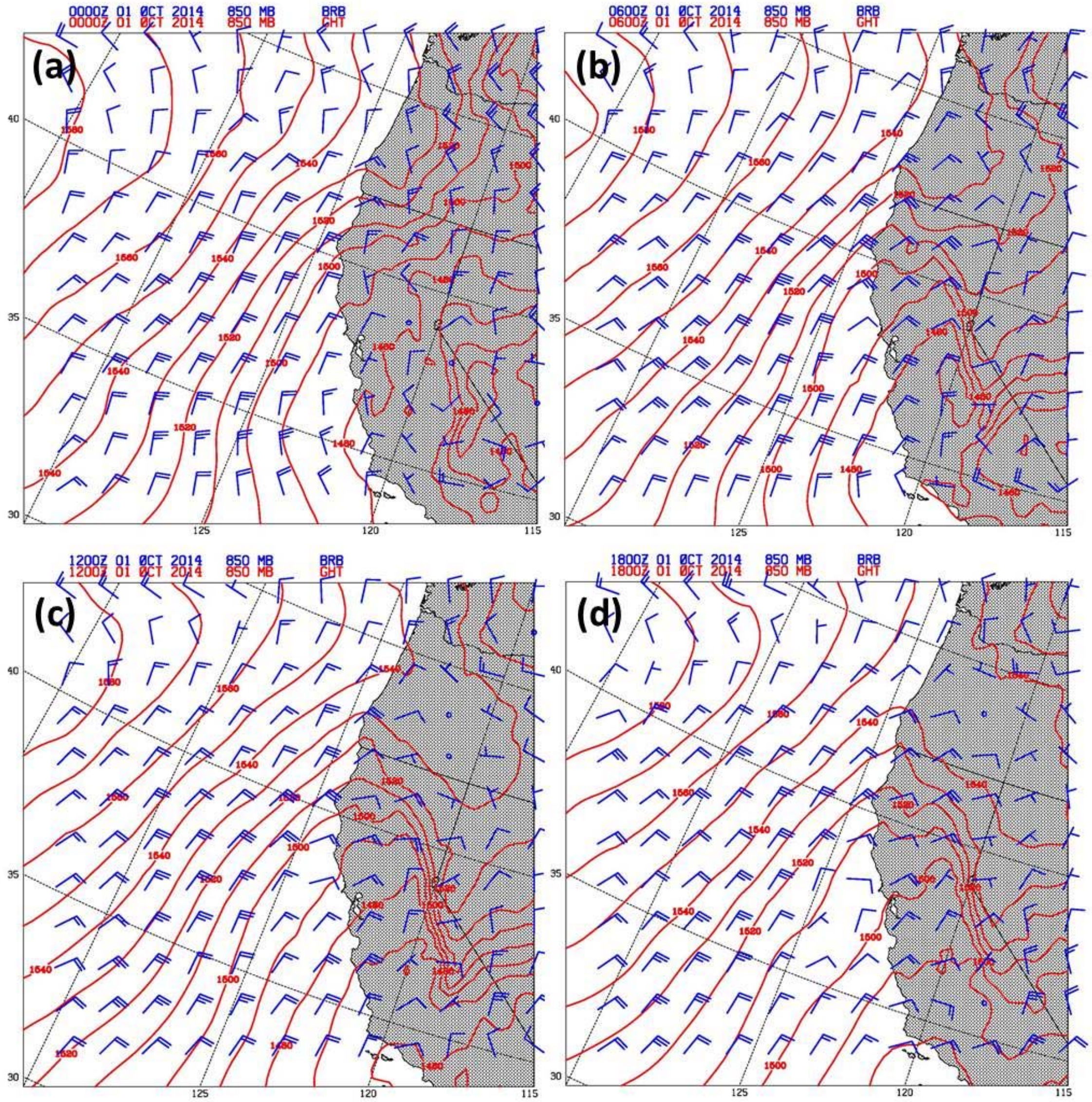


1600 (a) and 2000 (b) UTC 14 October 2013

4. October 01, 2014–Strong Northeasterly Flow

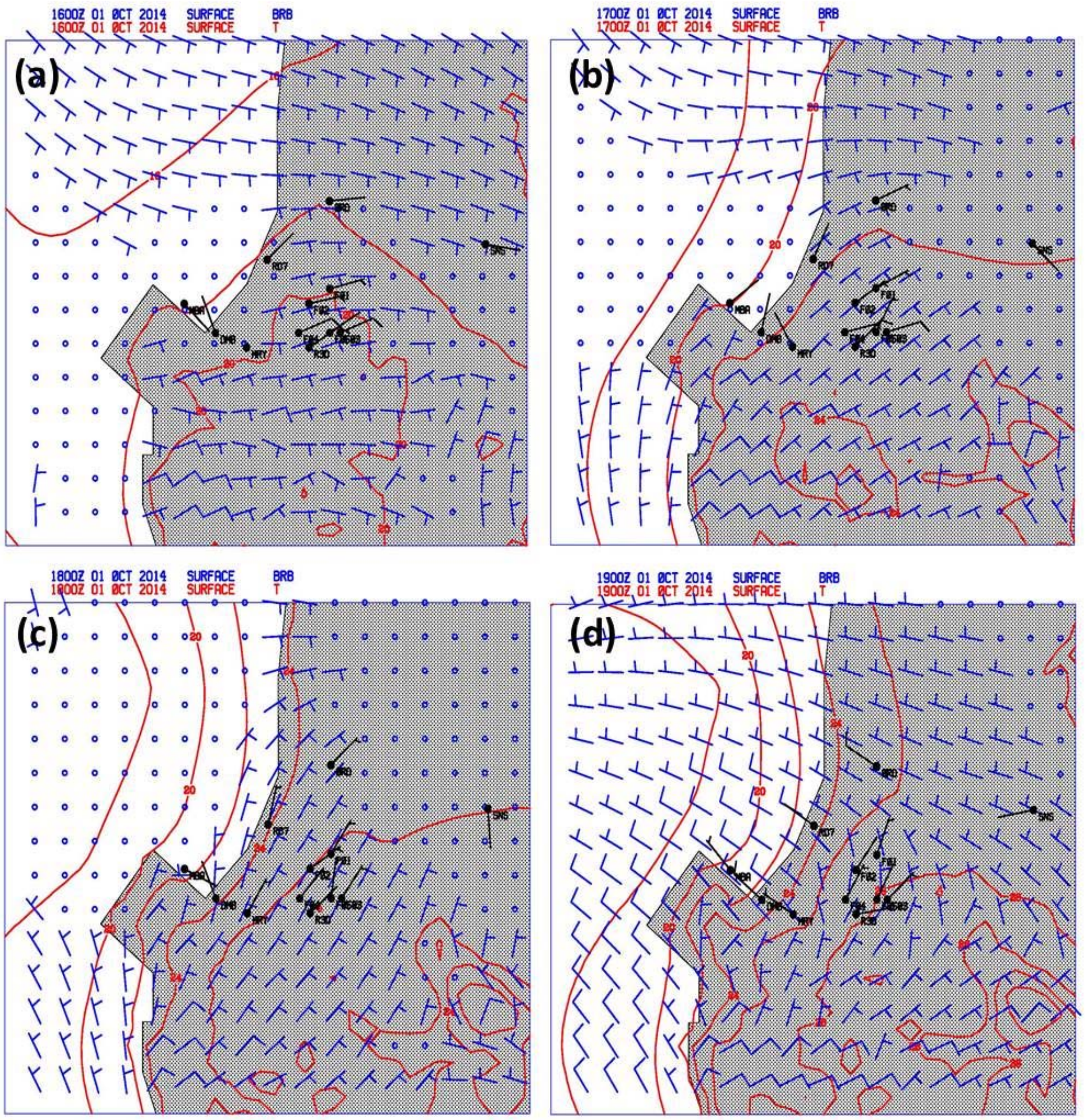
In of all the previous cases, the synoptic scale flow was rather weak. The October 01, 2014, case provides an example of stronger synoptic flow that also delays the sea breeze onset in the Monterey Bay area. As seen in Figure 23, a strong high pressure is present off the Northern California coast that results in tight packing of the geopotential heights lines (depicted in red) thus producing fairly strong 850 mb northeasterly flow. This flow is consistent in direction throughout the time frame from 0000 UTC through 1800 UTC and remains strong (15–30 knots) over this time as well. This synoptic scale structure changes the direction and magnitude of the synoptic scale flow compared to the previous case studies, but is able to produce the end result by delaying the sea breeze advancement into Fort Ord until 2000 UTC. The surface winds over the Monterey Bay region are primarily easterly at 1600 UTC (Figure 24a) but shift to northeasterly over the south portion over land by 1700 UTC (Figure 24b). The 1600 UTC flow direction suggests it is decoupled from the strong northeasterly flow 850 mb. As mixing occurs, the surface flow over the higher elevation over Fort Ord develops a northeasterly flow. This northeasterly flow is mostly coast parallel and produces very little offshore flow. Surface onshore flow starts by 1900 UTC (Figure 24d) but is confined to the immediate coast until 2000 UTC (Figure 26a). Figure 25a shows the character of the synoptic flow at 1600 UTC above the 900 mb level as a weak onshore flow at this time. The surface depicts a slight offshore breeze with calm transitional winds occurring at 950 mb. As the sea breeze develops by around 1900 UTC (Figure 25b) a weak offshore component develops above 900 mb as well as pronounced subsidence. This offshore flow and subsidence are consistent with the slight shift in the 850 mb flow to the east (Figure 23a) and flow descending the slope of the topography east of the Monterey Bay. This overall structure produces weak offshore flow that is strong enough to delay the sea breeze. However, once established, the sea breeze quickly strengthens into a deeper prominent onshore flow by 2000 UTC (Figure 26) with a strong cross coast thermal gradient. The subsidence seems to limit the depth of the sea breeze to be below 975 mb, much shallower than the previous cases.

Figure 23. 850 mb geopotential height and winds



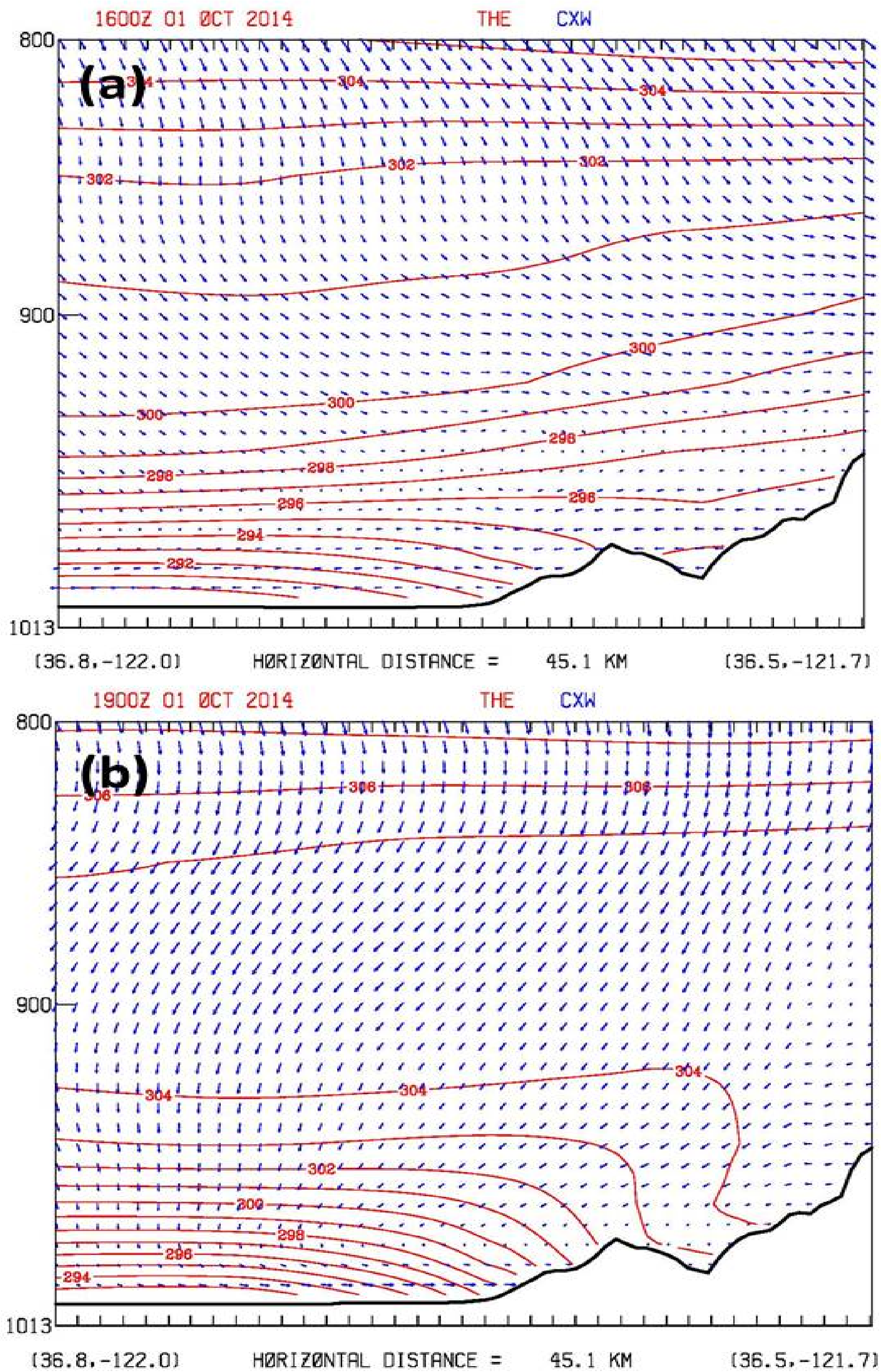
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 01 October 2014

Figure 24. Surface temperature and winds



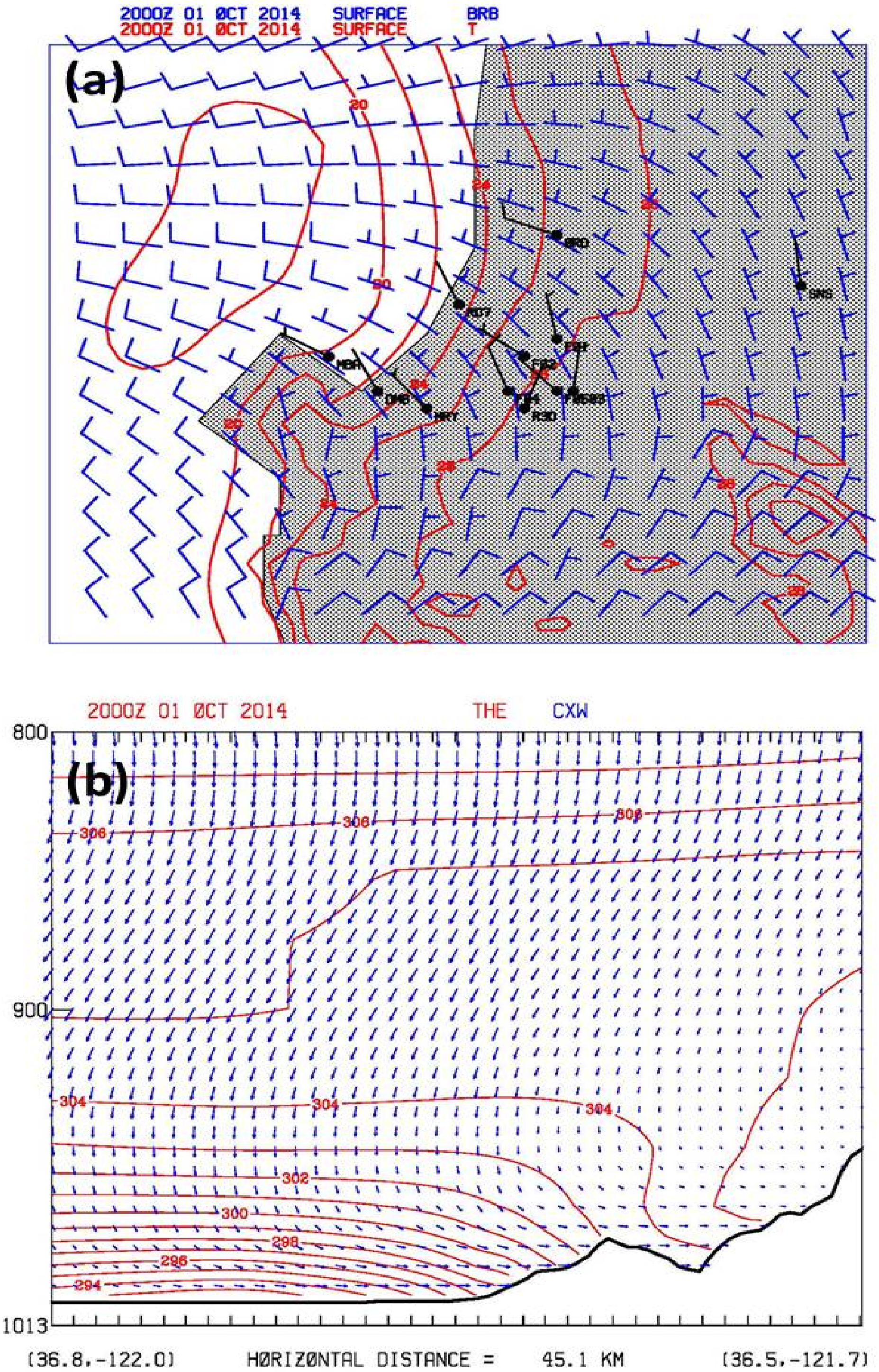
1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 01 October 2014

Figure 25. Potential temperature and winds in the plain of the cross section



1600 (a) and 1900 (b) UTC 01 October 2014

Figure 26. Surface and cross section plots



Surface temperature and winds (a) and potential temperature and winds in the plain of the cross section (b) at 2000 UTC 01 October 2014

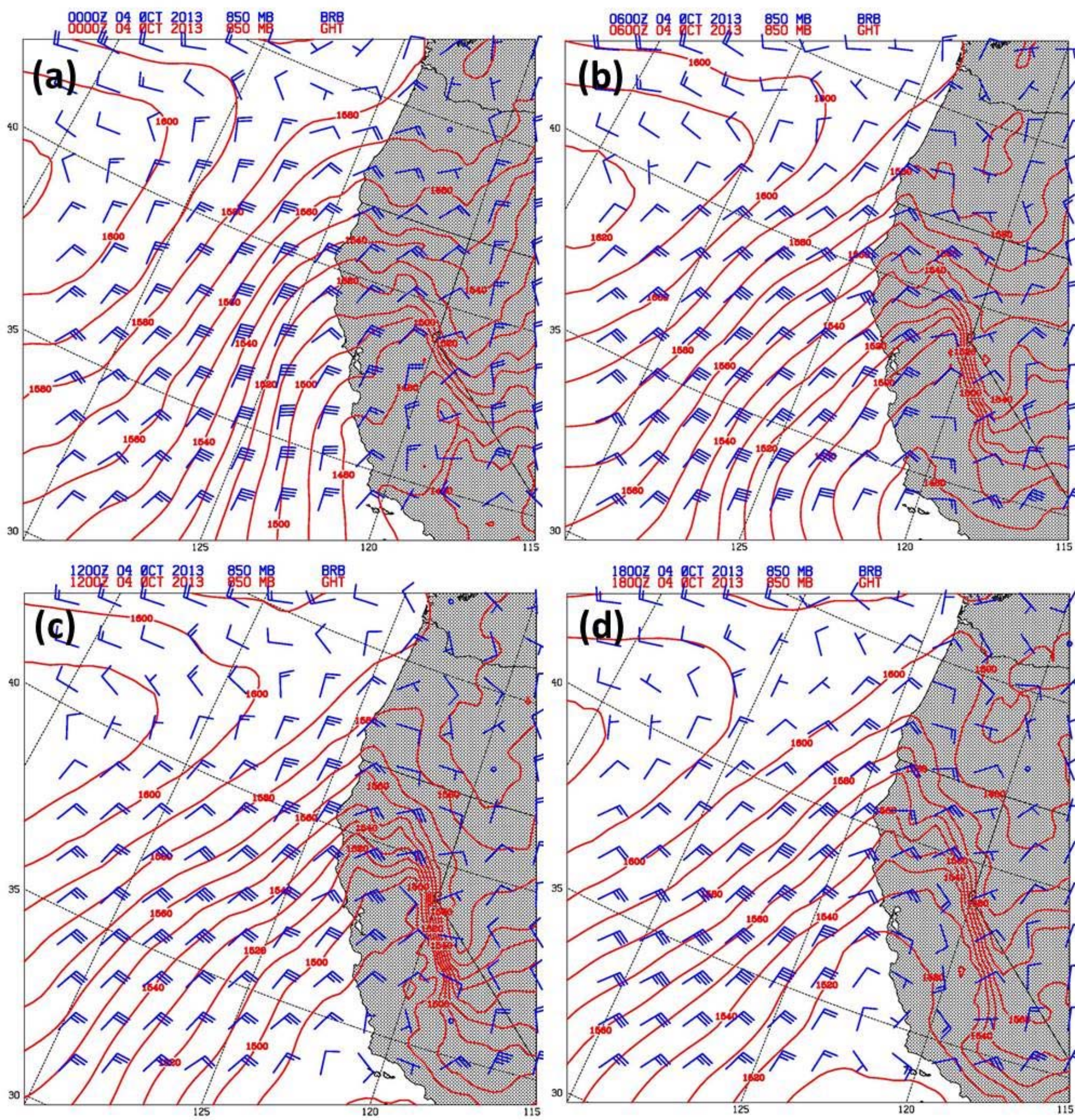
5. October 04, 2013–Very Strong Northeasterly Flow

October 04, 2013, produced the strongest synoptic scale flow that evolved over the day to delay the sea breeze until nearly 2200 UTC. High pressure is located west of Northern California featuring a strong zonal geopotential height gradient resulting in strong synoptic north-northeasterly flow of 25 knots into Fort Ord and the greater Monterey Bay region from 0000 UTC (Figure 27a) and 0600 UTC (Figure 27b). Figure 27c shows this flow pattern shifting to more easterly by 1200 UTC with the synoptic wind maintaining its strength. By 1800 UTC (Figure 27d), the synoptic flow over the Monterey Bay weakens and turns more easterly. This relaxation occurs as a localized ridge over the California coast in the morning is displaced as low pressure progresses northward to relax the strong geopotential height gradient over the Monterey Bay and decrease the wind speed from 25 knots to 5–10 knots and shift the winds easterly-southeasterly. As explained in the previous case study, this synoptic scale set up generates coast parallel surface flow as seen in all four panels of Figure 28. Figure 28 depicts the hourly mesoscale flow over the Monterey area from 1600 UTC through 1900 UTC with the 1600 UTC and 1700 UTC images showing northeasterly surface flow. By 1800 UTC (Figure 28c) and 1900 UTC (Figure 28d) the northeasterly flow is maintained as a cross coast thermal gradient develops with warming inland. The lack of turning of the surface flow onshore through 1900 UTC (Figure 28d) is consistent with the shift in the 850 mb flow to the east which opposes the development of the sea breeze.

The shift in synoptic scale winds to easterly-southeasterly is most evident in comparing the cross section at 1600 UTC (Figure 29a) to 2200 UTC (Figure 29b). For Figure 29a, the synoptic flow at 1600 UTC above 900 mb is weakly onshore with a weak land breeze apparent at the surface. In contrast, Figure 29b at 2200 UTC depicts offshore flow above 900 mb resulting from the synoptic wind shift. Of note, these winds are enhanced due to the already established sea breeze circulation at the surface providing additional return flow in the offshore direction above 900 mb. The horizontal surface flow in Figure 30 shows a distinct sea breeze front just west of Fort Ord at 2100 UTC (Figure 30a) and, within an hour at 2200 UTC (Figure 30b), the sea breeze front

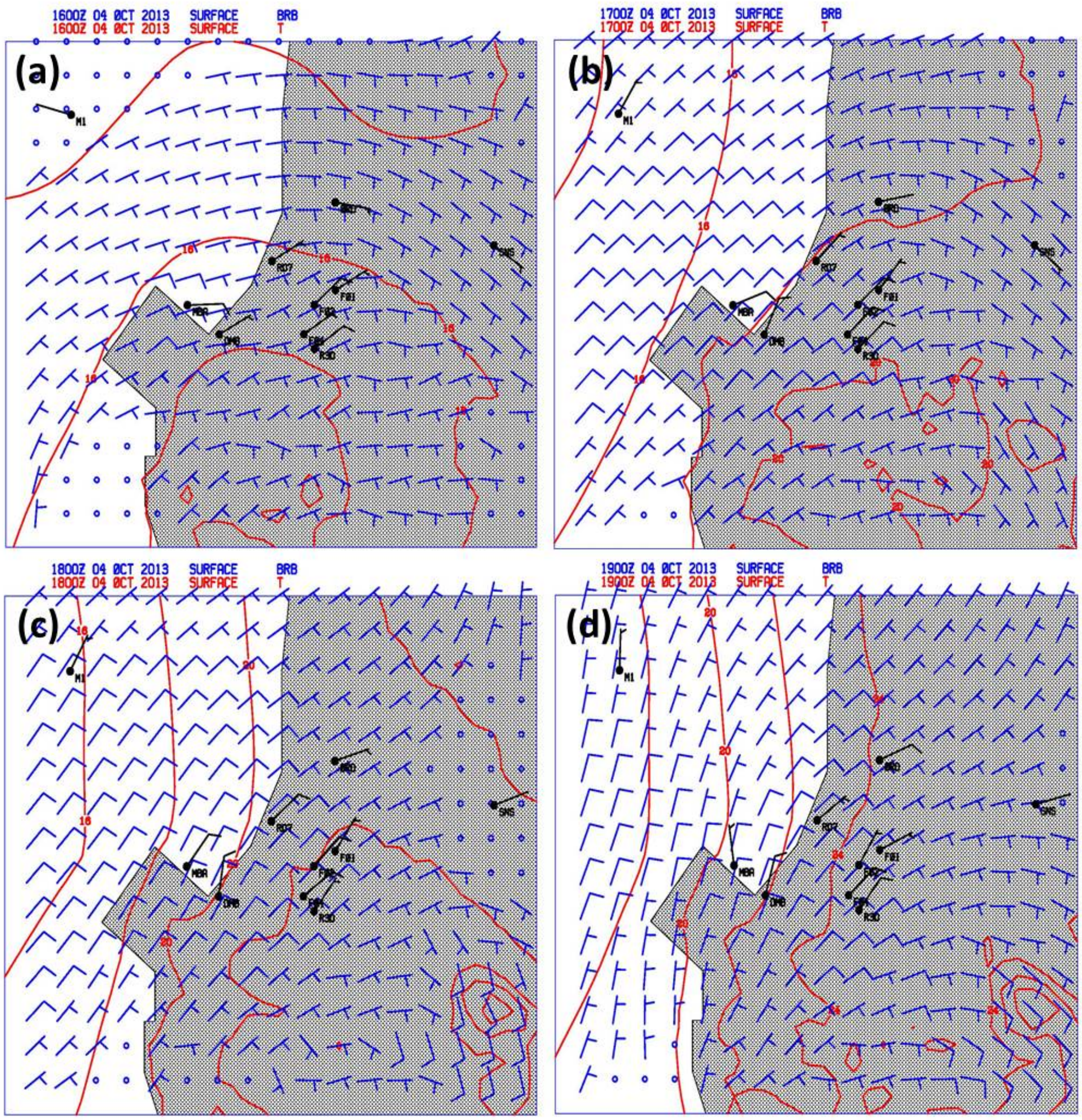
progresses throughout Fort Ord producing pronounced onshore flow over the Monterey region extending into Salinas.

Figure 27. 850 mb geopotential height and winds



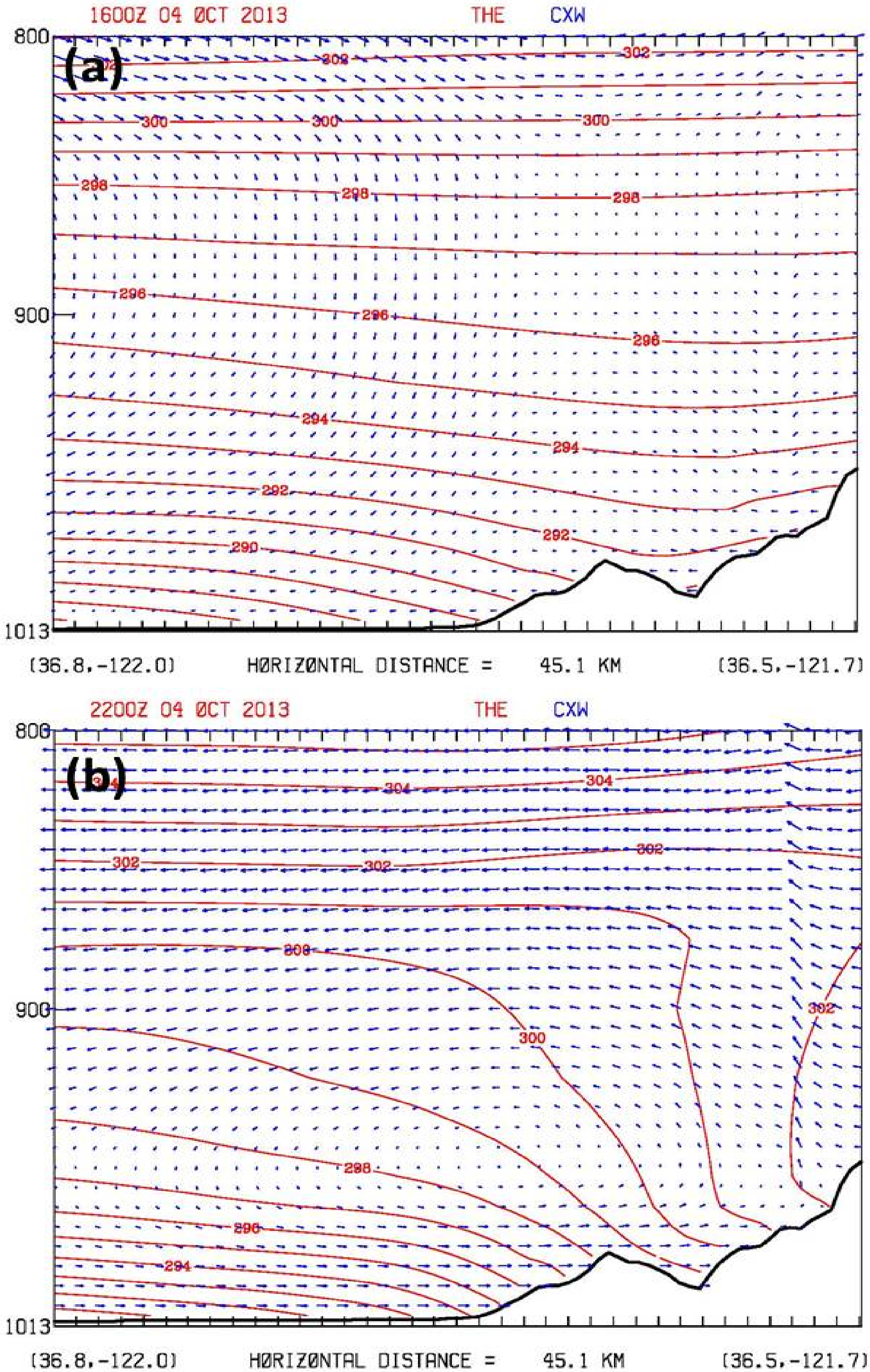
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 04 October 2013

Figure 28. Surface temperature and winds



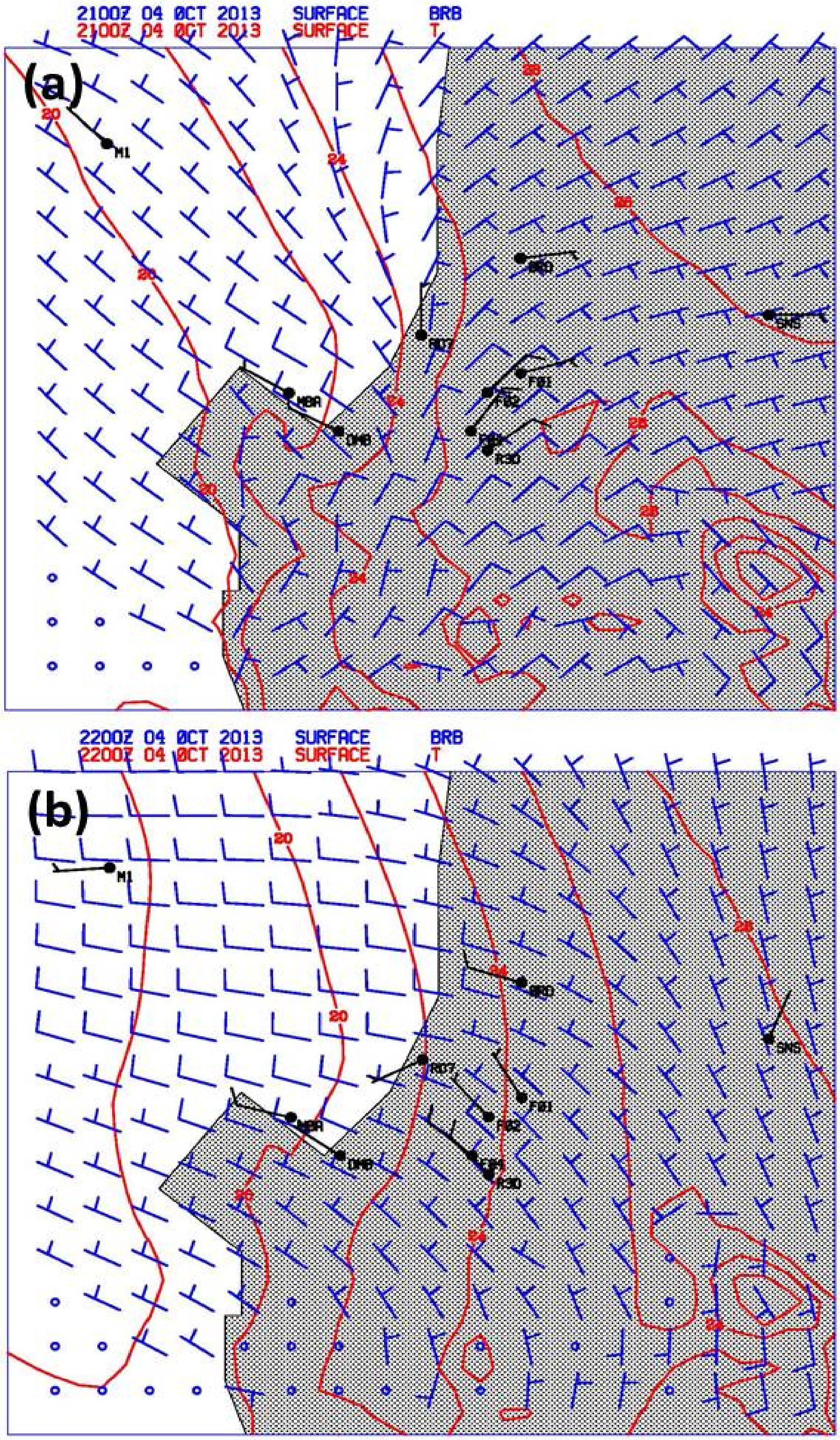
1600 (a), 1700 (b), 1800 (c) and 1900 UTC 04 October 2013

Figure 29. Potential temperature and winds in a cross section



1600 (a), and 2200 (b) UTC 04 October 2013

Figure 30. Surface temperature and winds



2100 (a) and 2200 (b) UTC 04 October 2013

B. STATIC STABILITY INFLUENCE

Two of the 12 cases appear to have a delayed sea breeze onset due to the influence of static stability. As noted by Estoque (1962) and Arritt (1993), increased static stability tends to dampen sea breeze circulations and can therefore delay the onset. The background synoptic flow differed between these cases but did not appear to be the primary factor in sea breeze delay. In both cases, sea breeze onset was delayed until about 1900–2000 UTC.

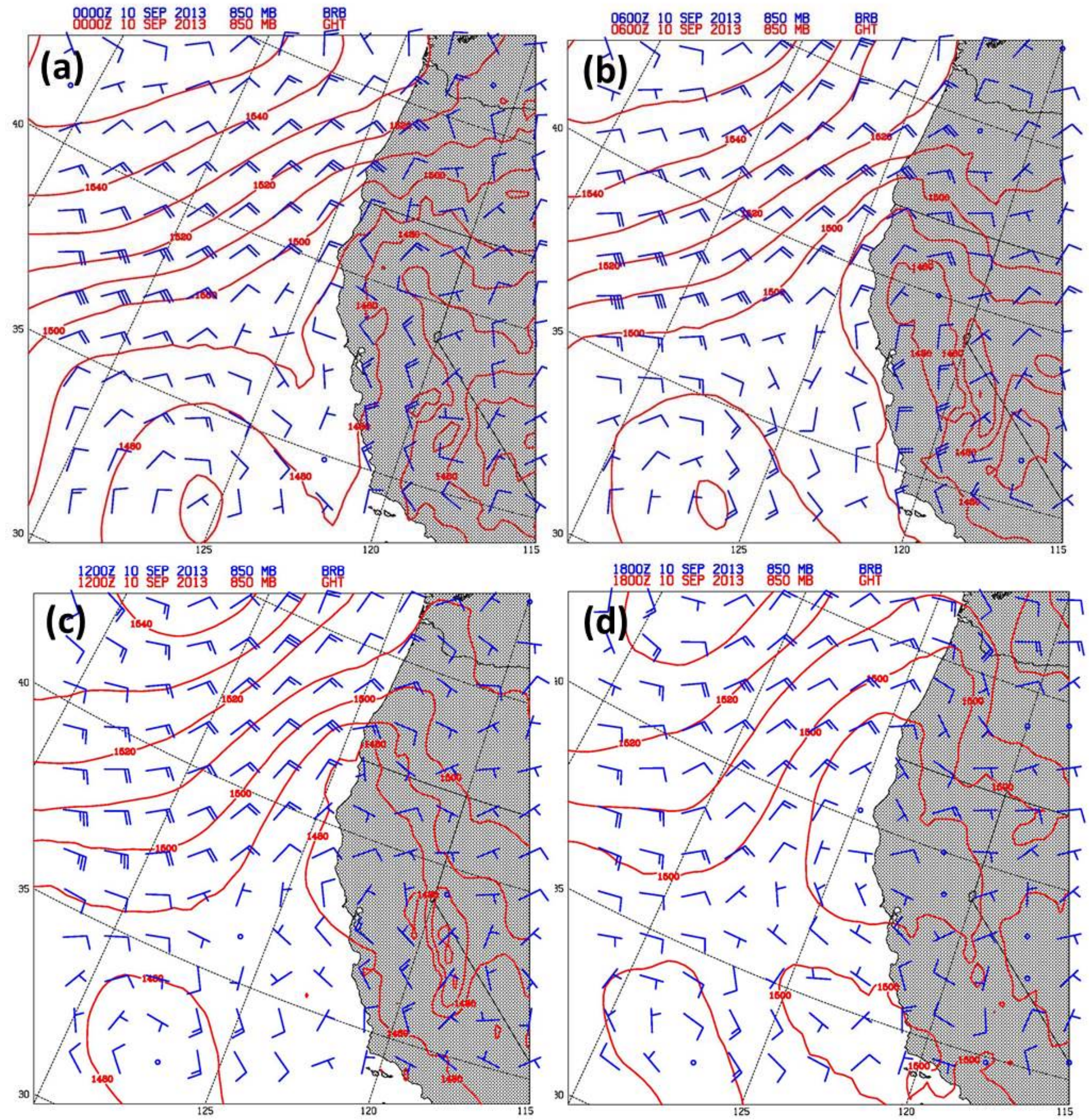
1. September 10, 2013

On September 20, 2013, high pressure is located off the Pacific Northwest coast with weak low pressure off the southern coast of California. Figure 30 shows the evolution of the 850 mb synoptic flow from 0000 UTC to 1800 UTC on 10 September, where low pressure develops over the Northern California coast by 1800 UTC (Figure 30d). As a result of the low over the Northern California coast, the flow around the Monterey Bay area is light and northwesterly during 1200 UTC (Figure 30c) and 1800 UTC (Figure 30d). This onshore flow would lead one to initially conclude that the synoptic flow will enhance the localized sea breeze vice delaying it. However, this synoptic pattern is actually associated with initiating a coastal wind reversal (Nuss et al. 1999) where the along-coast surface flow is southerly instead of northwesterly. Figure 31a depicts southerly surface flow outside the bay at 1600 UTC and a light land breeze beginning at the coastline out towards the Monterey Bay with calm and variable winds further inland around Fort Ord. Additionally, there is no substantial surface temperature gradient across the coast or inland at this time. The 1600 UTC cross section in Figure 32a illustrates the vertical structure with strong static stability occurring from the surface to the 900 mb level across the entire cross section. This structure is indicative of a shallow marine layer capped by a very strong inversion, which again is associated with a coastal wind reversal (Nuss et al. 1999). Above 900 mb the synoptic onshore flow in the direction of the cross section is consistent with the 850 mb northwesterly flow. The static stability prevents its influence reaching the levels below 900 mb. Therefore, the diurnal land breeze circulation developed from overnight and early morning is still quite apparent

with downward circulation over Fort Ord, offshore flow at the surface out into the Monterey Bay. Thus the static stability is de-coupling the synoptic scale flow at 850 mb from the local flow.

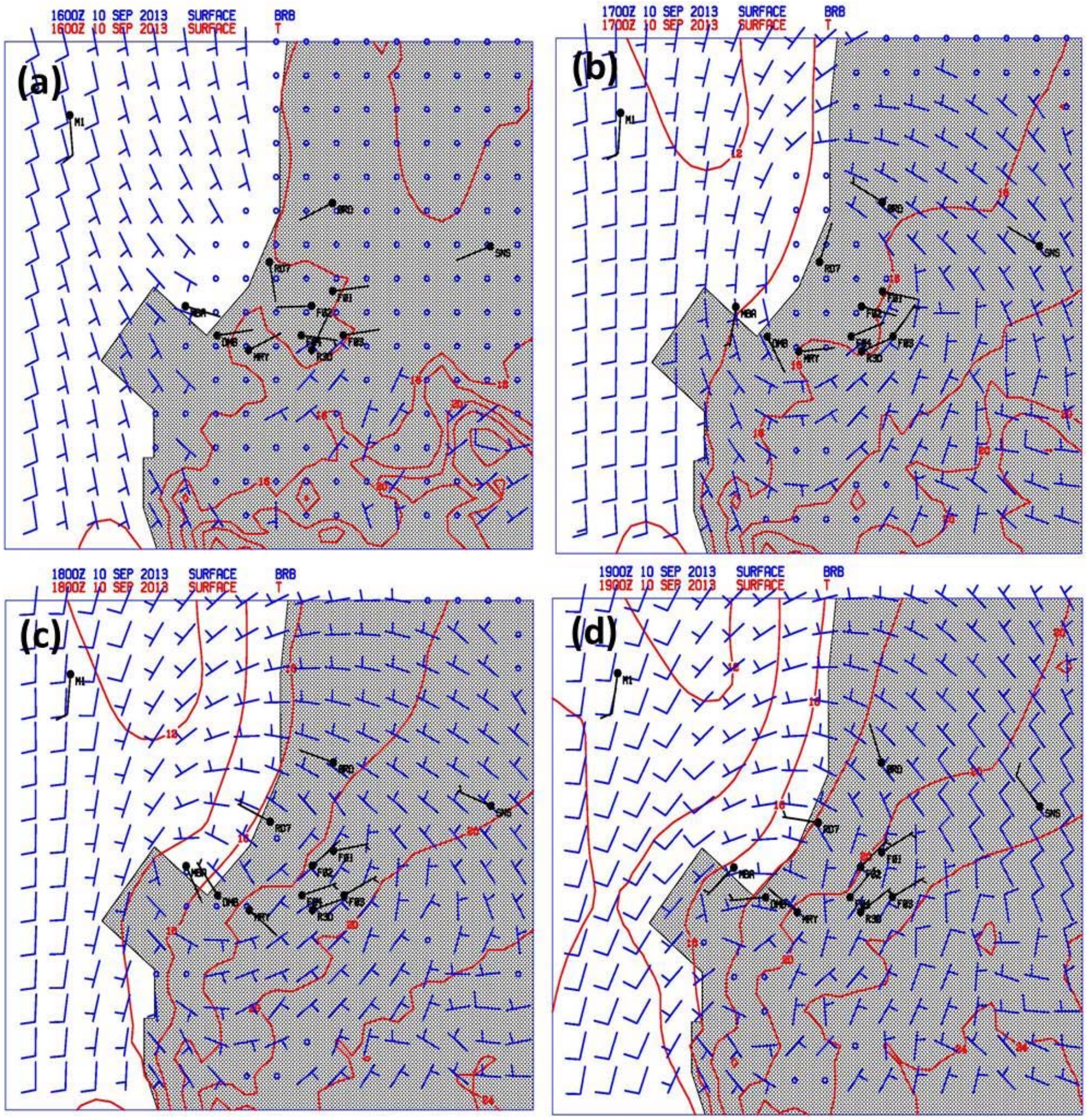
The necessary cross-coast temperature gradient to excite a sea breeze and rotate the flow onshore develops by 1900 UTC in Figure 31d, with light onshore flow along the coast slowly progressing inward with a counterclockwise turning of the winds through the north at the Fort Ord location. The 1900 UTC cross section (Figure 33b) illustrates the cross-coast static stability relaxing, allowing for a temperature gradient to develop across the coast as well as inland at the surface. Above the surface and the strong static stability layer, the synoptic scale northwesterly flow is maintained even though a sea breeze is beginning to develop. The 1900 UTC surface analysis (Figure 32d) shows the sea breeze penetrating inland somewhat but northeasterly flow is present over most of the Fort Ord region. This northeasterly flow represents an anticyclonic gyre setup in the southern part of the Monterey Bay due to the anticyclonic shear associated with the wind reversal. This circulation helps to maintain northeasterly flow over Fort Ord even with a sea breeze starting to develop. Eventually, the sea breeze northwesterly surface flow penetrates the Fort Ord region.

Figure 31. 850 mb geopotential height and winds



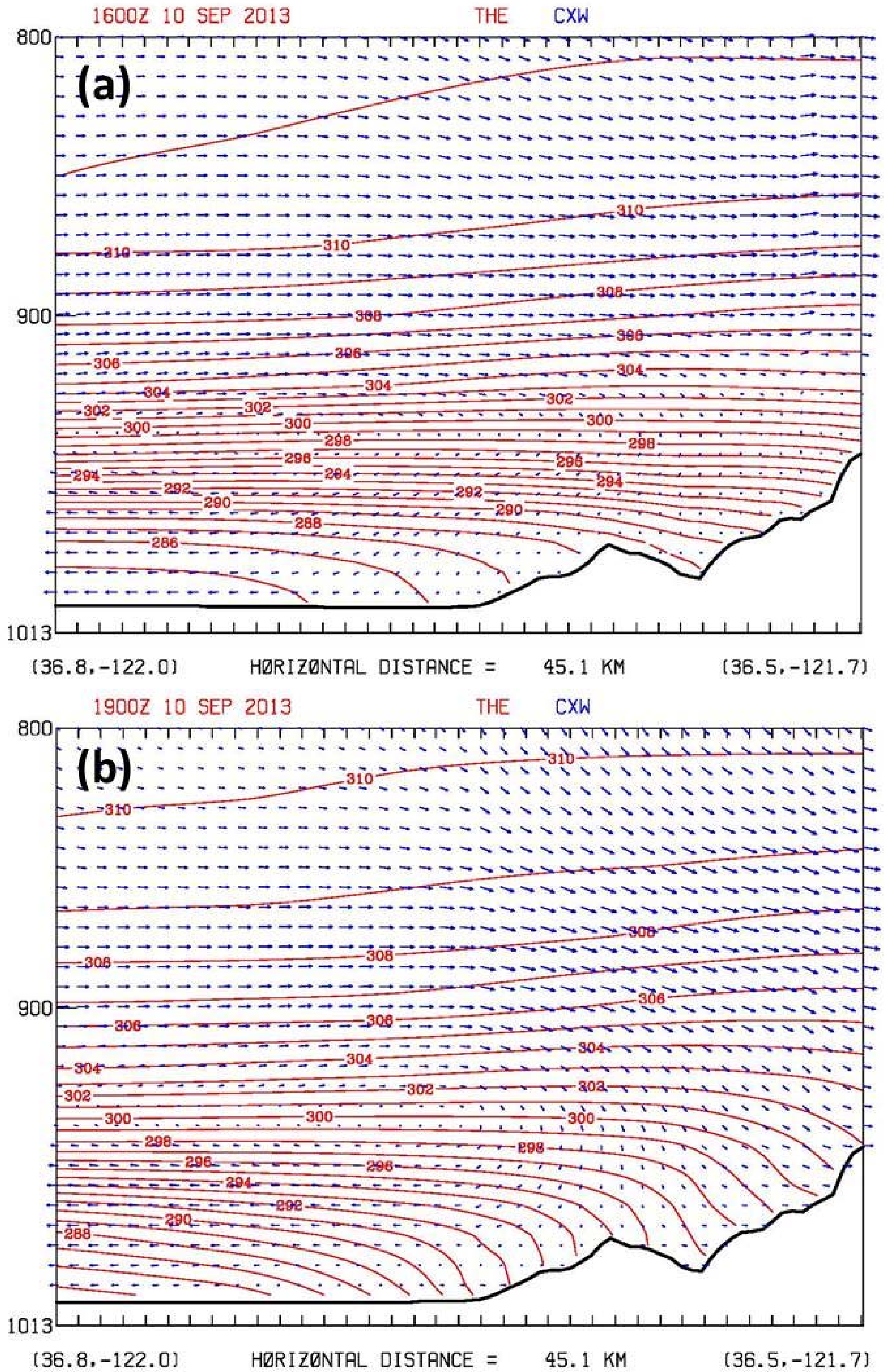
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 10 September 2013

Figure 32. Surface temperature and winds



1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 10 September 2013

Figure 33. Potential temperature and winds in a cross section



1600 (a) and 1900 (b) UTC 10 September 2013

2. November 01, 2013

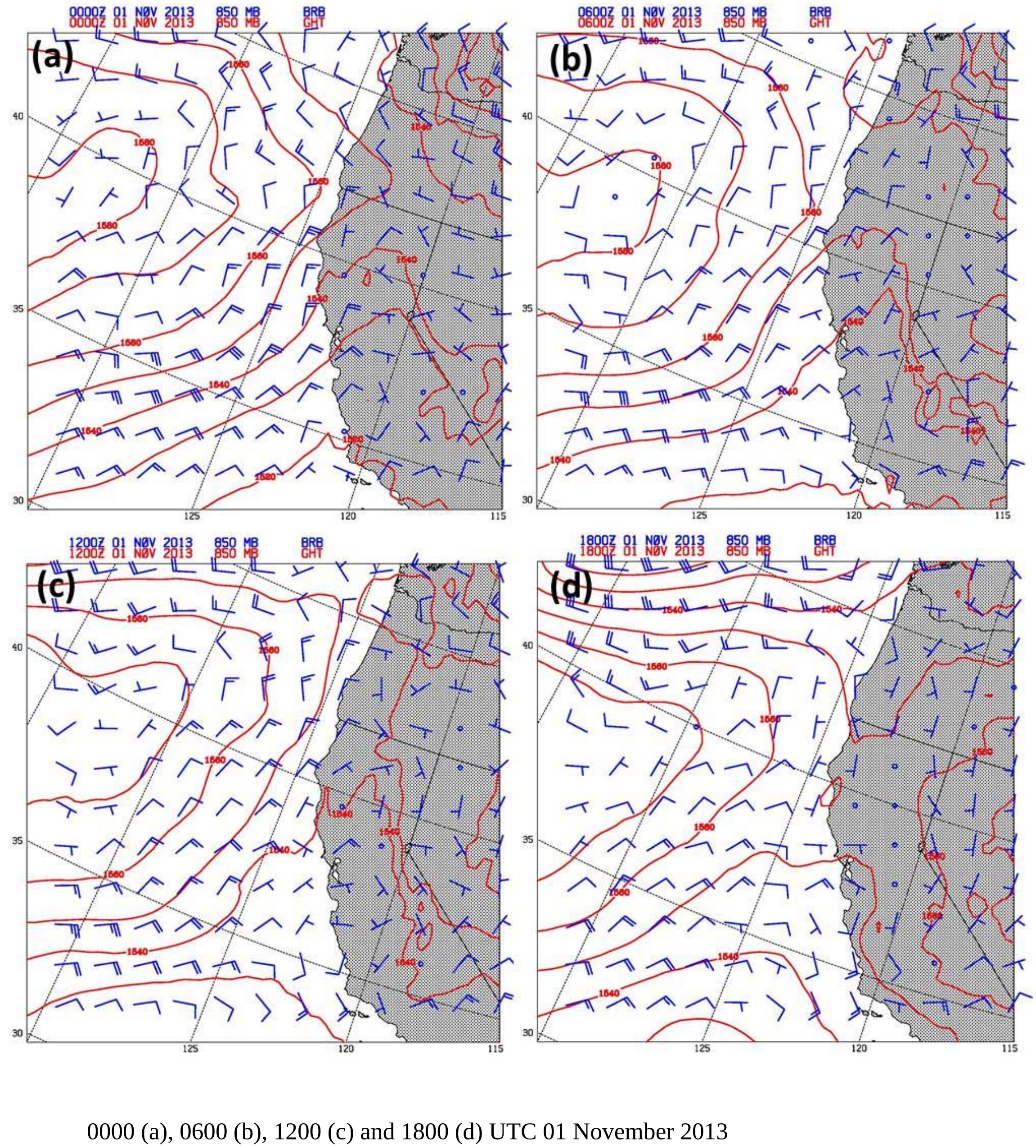
November 01, 2013 illustrates another example of the impact of static stability on the sea breeze onset unlike the previous case where a wind reversal occurred. Figure 33 depicts high pressure located off the Northern California coast with low pressure moving toward Southern California in the second half of the time period. At 0000 UTC (Figure 34a) and 0600 UTC (Figure 34b), the Monterey Bay area is under northeasterly flow associated with the high pressure to the northwest. As the pressure systems interact at 1200 UTC (Figure 34c), the Monterey Bay region has light easterly winds just north of the Monterey Bay and light westerly winds just south of the Monterey Bay. Thus, the resultant synoptic scale winds in the area of interest are negligible as seen at 1200 UTC from Figure 34c. By 1800 UTC (Figure 34d), the 850 mb winds become southeasterly and are orientated parallel to the Salinas Valley. Figure 35a shows the surface winds at 1600 UTC directed offshore across the entirety of Fort Ord. Specifically enhanced surface winds are apparent east of Fort Ord oriented in the southeast-northwest direction resulting from funneling of the synoptic scale winds through the Salinas Valley. This topographic feature plays an important role at the NPS Profiler located at Marina. As noted in the 1700 UTC (Figure 35b), 1800 UTC (Figure 35c) , and 1900 UTC (Figure 35d) images, the winds observed at the NPS Profiler are not an accurate representation of the observed winds located at Fort Ord. For example, the 1900 UTC surface winds (Figure 35d) depict light offshore winds while Fort Ord observations for the same time depict light onshore flow from the sea breeze onset.

The 1600 UTC cross section from Figure 36a illustrates offshore flow from not only the surface but throughout the vertical column extending from the surface to the 800 mb level. No clear land breeze circulation pattern exists as the majority of the cross sectional offshore flow is in the same direction and is consistent with a synoptic scale southeasterly flow. Figure 36a at 1600 UTC also shows isothermal conditions at most of the vertical levels with nearly flat isentropes over the cross section. Between 1600 UTC and 1900 UTC (Figure 36b) a slightly increased cross coastal thermal gradient develops in the low levels which works to initiate the sea breeze. Interestingly enough, by 1900 UTC, Figure 35d observations show onshore winds while the coast exhibits more of an

along coast orientation of the flow directed northeasterly. Thus 1900 UTC exhibits a non-classical sea breeze type flow inland but not at the coast. Figure 36b also illustrates a light sea breeze circulation developing at 1900 UTC from the surface to 950-mb with onshore flow inland and lightly upward flow near the coast. Specifically, the 1900 UTC analysis (Figure 35d) shows the Salinas Valley offshore flow north of Fort Ord turning more coast parallel as opposing flow develops at the coast. At the same time, the flow over Fort Ord has turned onshore as a weak sea breeze. Thus while these are only approximately 10 miles separation between the Fort Ord and the NPS Profiler sites, vastly different flows exist. Another important parameter to note in this case is the weak temperature gradient across the coast. With the temperature over the ocean (64°F) only 8° different from inland (72°F) temperatures, the sea breeze takes longer to develop and is not as pronounced. This lack of warming over the land is the result of the static stability limiting the temperature rise.

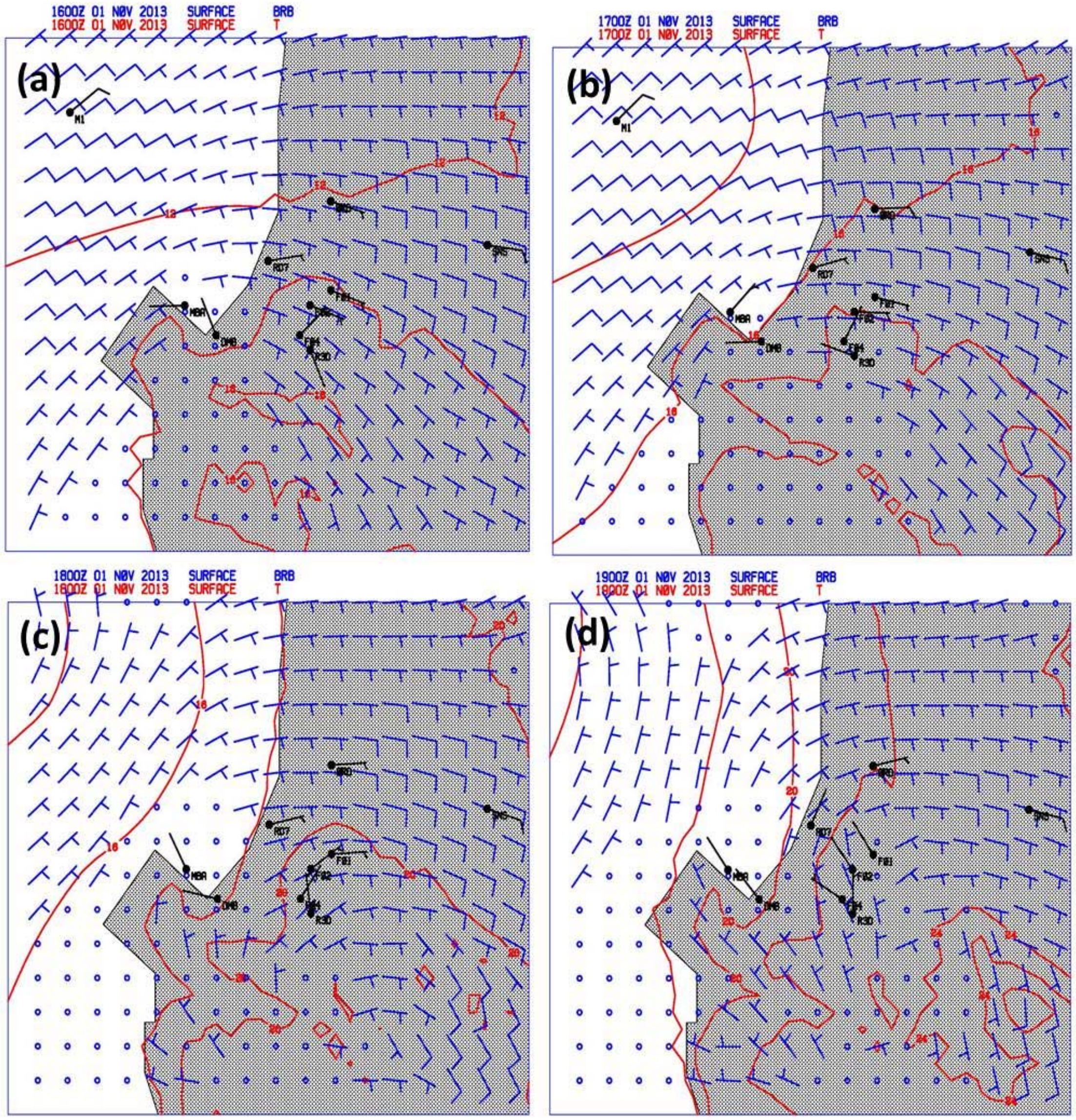
Both cases presented in this section provide support for delayed sea breeze onset due to the presence of strong static ability. While the end result was the same, characteristics of each case were quite different. Case #1 possessed stronger static stability in the vertical than Case #2. Additionally, the cross coast surface temperature gradient for Case #1 was 15°F (57°F–72°F) while Case #2 was nearly half that at 8°F (64°F–72°F). Thus while both cases reached the same inland temperatures, the Case #1 temperature gradient promoted stronger cross coast forcing but the stronger static stability delayed sea breeze onset due to its impact on vertical motion that slowed development of the full sea breeze circulations. In contrast, the weaker static stability of Case #2 resulted in the same timing of sea breeze onset even with a weaker temperature gradient. The weaker static stability allowed a stronger vertical circulation that aided sea breeze onset. As a result, these cases illustrate how static stability impacts vertical motion to influence the time of sea breeze onset.

Figure 34. 850 mb geopotential height and winds



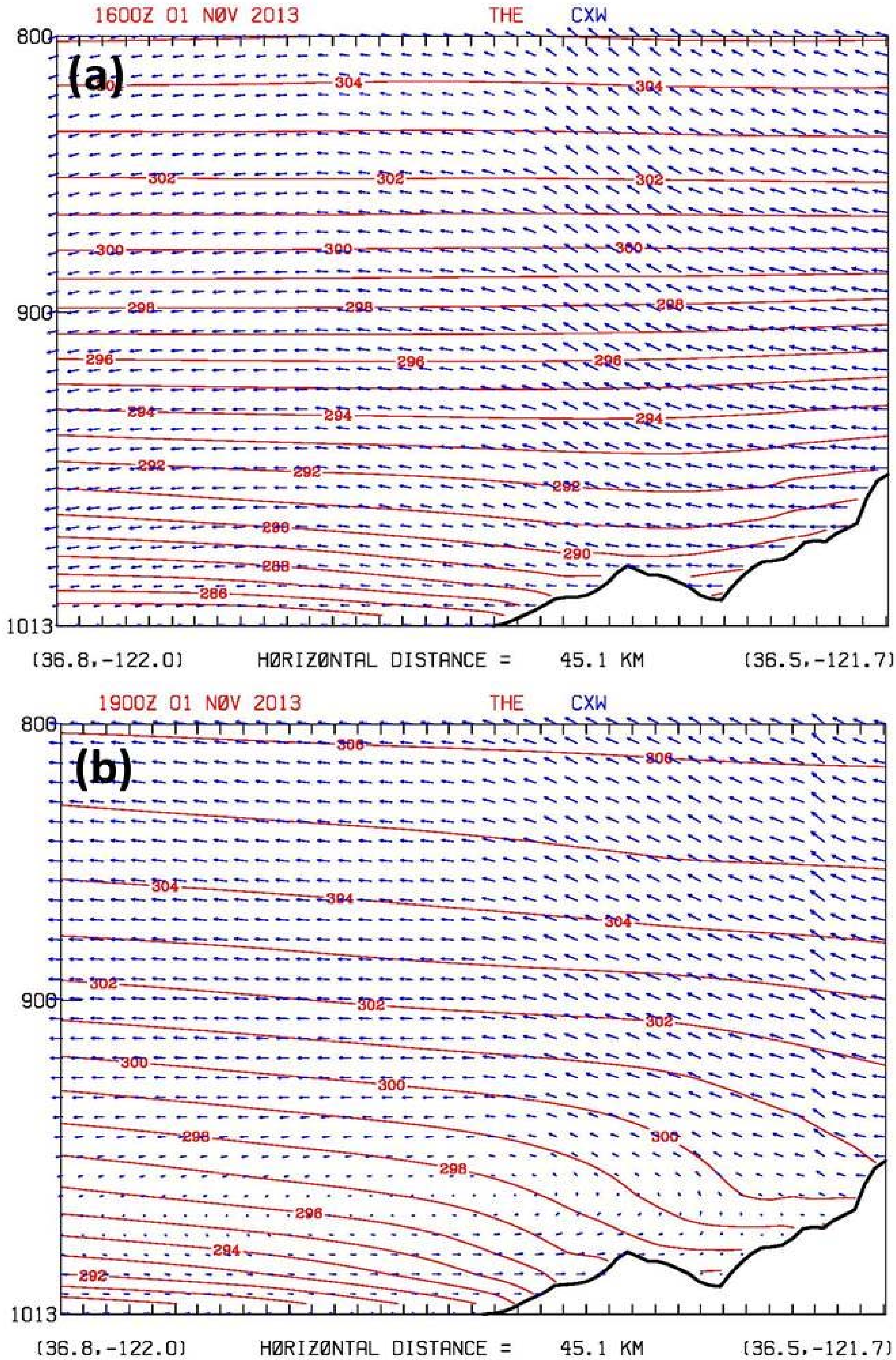
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 01 November 2013

Figure 35. Surface temperature and winds



1600 (a), 1700 (b), 1800 (c) and 1900 (d) UTC 01 November 2013

Figure 36. Potential temperature and winds in a cross section



1600 (a) and 1900 (b) UTC 01 November 2013

C. TEMPERATURE GRADIENT INFLUENCE

One of the 12 cases appears to have a delayed sea breeze onset due to the absence of a temperature gradient. As noted by Nuss (2003), Wallace and Hobbs (2006), and Gahmberg et al. (2009), the sea breeze is a thermal induced circulation resulting from the cross coast thermal gradient. Hence, stronger thermal gradients should produce stronger sea breeze circulations and the opposite holds true for weak thermal gradients. Therefore, the absence of a thermal gradient should weaken and/or delay the sea breeze onset. In this case, sea breeze onset was delayed until about 2000–2100 UTC. Specifically, November 21, 2013, depicts the influence of an absent temperature gradient.

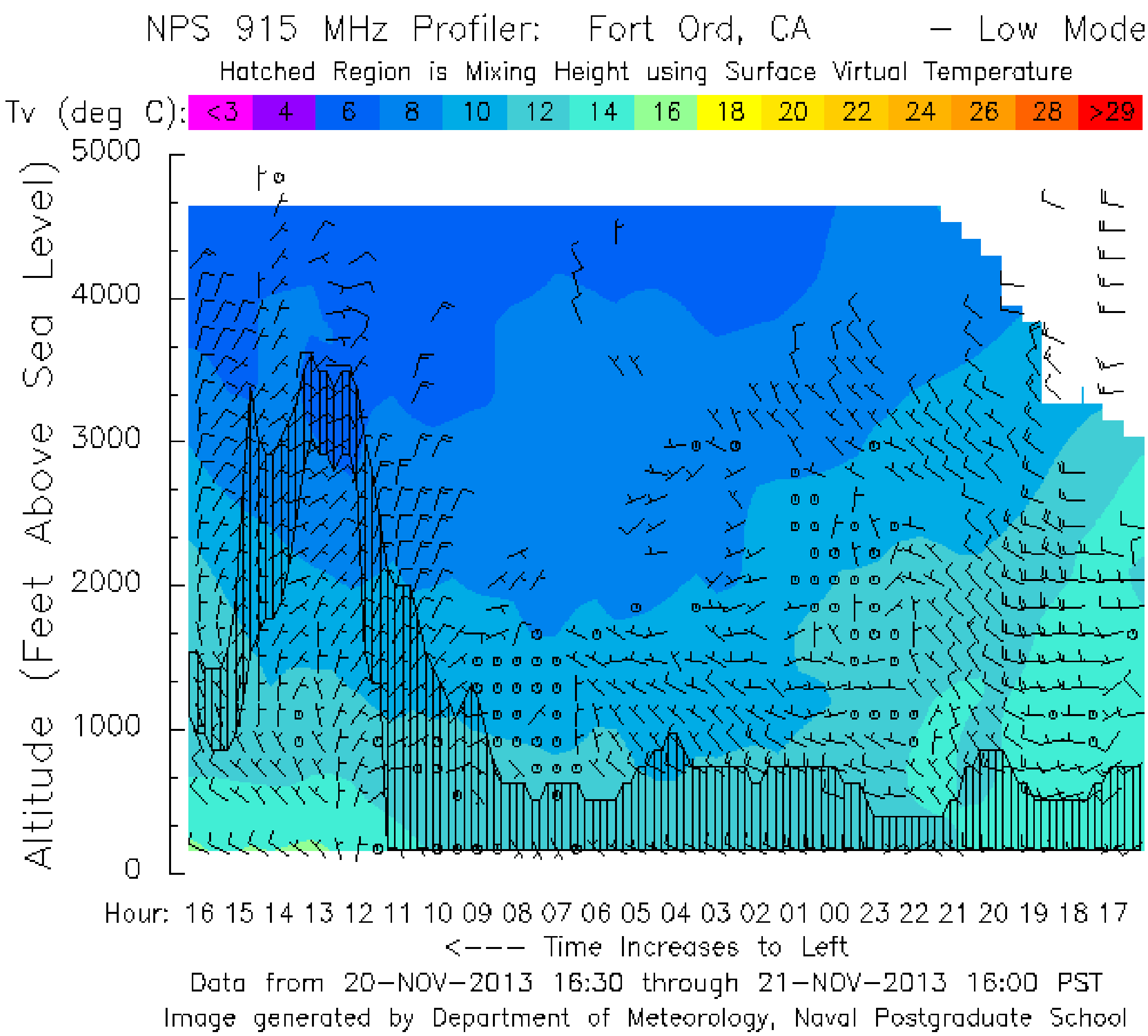
Of particular interest in this case is the lack of temperature contrast between the ocean and land temperatures. Specifically, Figure 37 shows the temperature range at the NPS Profiler for November 21, 2013 of 54°F–57°F (12°C–14°C) throughout the day which equates roughly to the November average water temperature of 56°F for the Monterey Bay. Consequently, the necessary ocean-land temperature gradient to drive a sea and land breeze is non-existent. Synoptically, Figure 38 shows low pressure situated inland of Monterey, California, and moving slightly south into Southern California by 1800 UTC (Figure 38d). The 850 mb flow remains fairly constant in a northerly direction around 10 knots through 1200 UTC (Figure 38c). The winds shift slightly northeasterly and strengthen to 15 knots at 1800 UTC (Figure 38d). While this structure should provide additional onshore flow to support the development of the sea breeze due to Coriolis effects, the mesoscale flow at the surface is quite different.

The 1600 UTC through 1900 UTC mesoscale analysis (Figure 39) depict light and variable flow in the Monterey Bay and Fort Ord regions with a distinct pattern emerging. Weak northwesterly flow is evident offshore from Monterey Bay over the entire period consistent with the synoptic flow. Very weak offshore to coast parallel flow develops over the Fort Ord area through the day. Additionally, Figure 39 also shows minor temperature increases from the Monterey Bay inland through Fort Ord of only 2°F–3°F, which is consistent with the lack of an onshore sea breeze by 1900 UTC (Figure 39d). The 1600 UTC cross section from Figure 40a shows no thermal gradient in the 900 mb to 800 mb layer with only a slight thermal gradient at the surface. The slight one- to two-

degree potential temperature difference from the land to ocean creates a weak land breeze circulation. Additionally, surface convergence occurs in the Monterey Bay moving winds vertically aiding the recirculation of the land breeze. By 1900 UTC (Figure 40b), a definitive cross-coast thermal gradient of approximately 3°F develops in the onshore direction in the surface to the 900 mb layer. Consequently, mixing occurs between the surface and synoptic flow with northwesterly flow inland from Fort Ord near the Salinas Valley. A weakened land breeze over Fort Ord coastward into the Monterey Bay as also represented in the 1900 UTC surface analysis in Figure 39a. By 2000 UTC, the synoptic flow (Figure 41a) and cross-coast thermal gradient combine to establish the sea breeze onset throughout the cross section at the surface level. As a result, the cross section illustrates strong support from the synoptic flow (Figure 41b) as the 900 mb to 800 mb wind is transported into the lower levels influencing the surface flow.

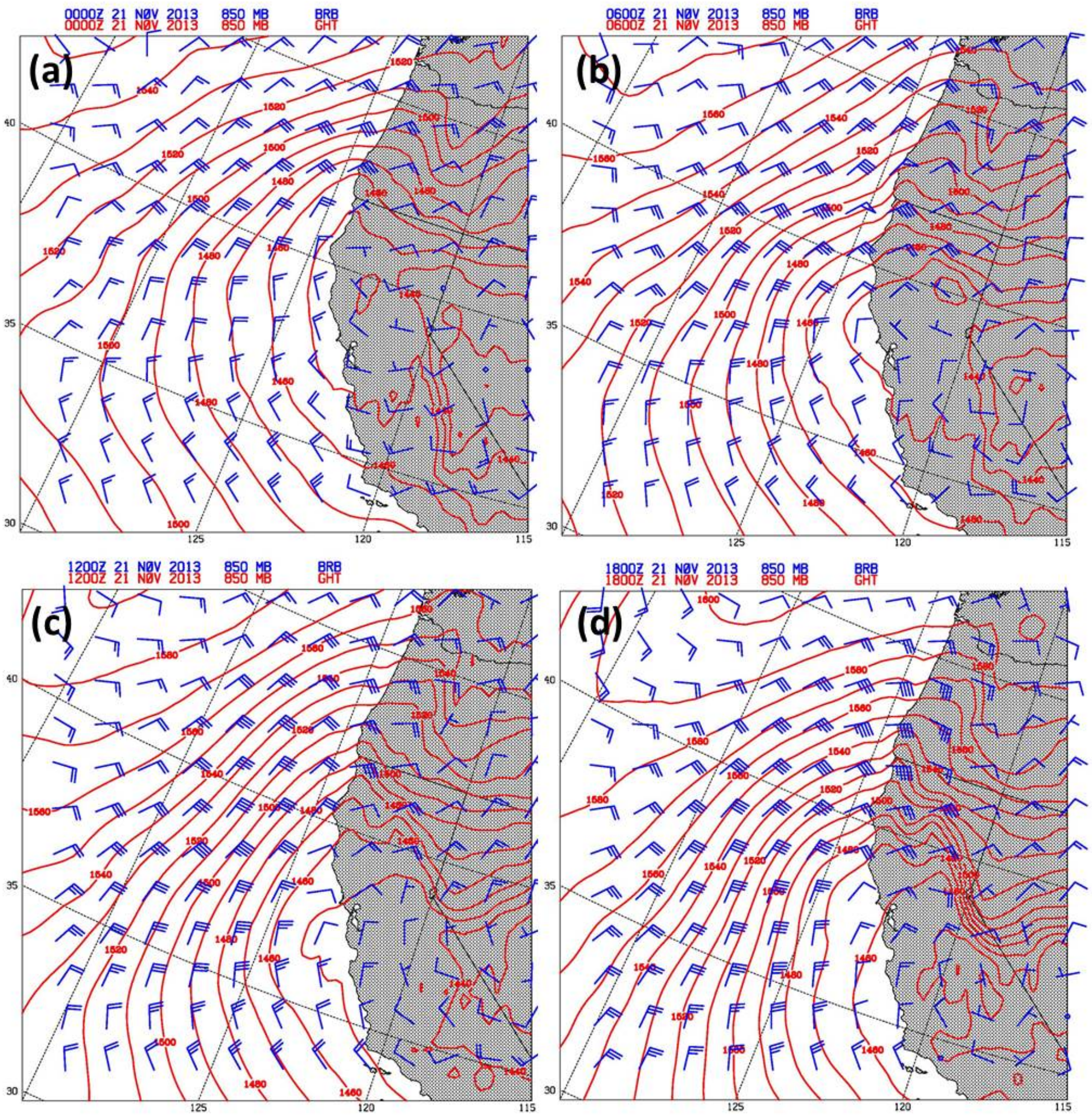
This case once again shed light on the importance of understanding additional features influencing the dynamics of the sea breeze onset. Even with the steady support of synoptic flow supporting the production of the sea breeze, it was unable to develop in the absence of a cross-coast thermal gradient—specifically, ambient temperatures which remain consistent with the ocean temperature eliminate temperature gradients. Additionally, only a 2°F–3°F cross-coast temperature gradient was sufficient in order to begin the process to enable a sea breeze to develop.

Figure 37. NPS Profiler at Fort Ord



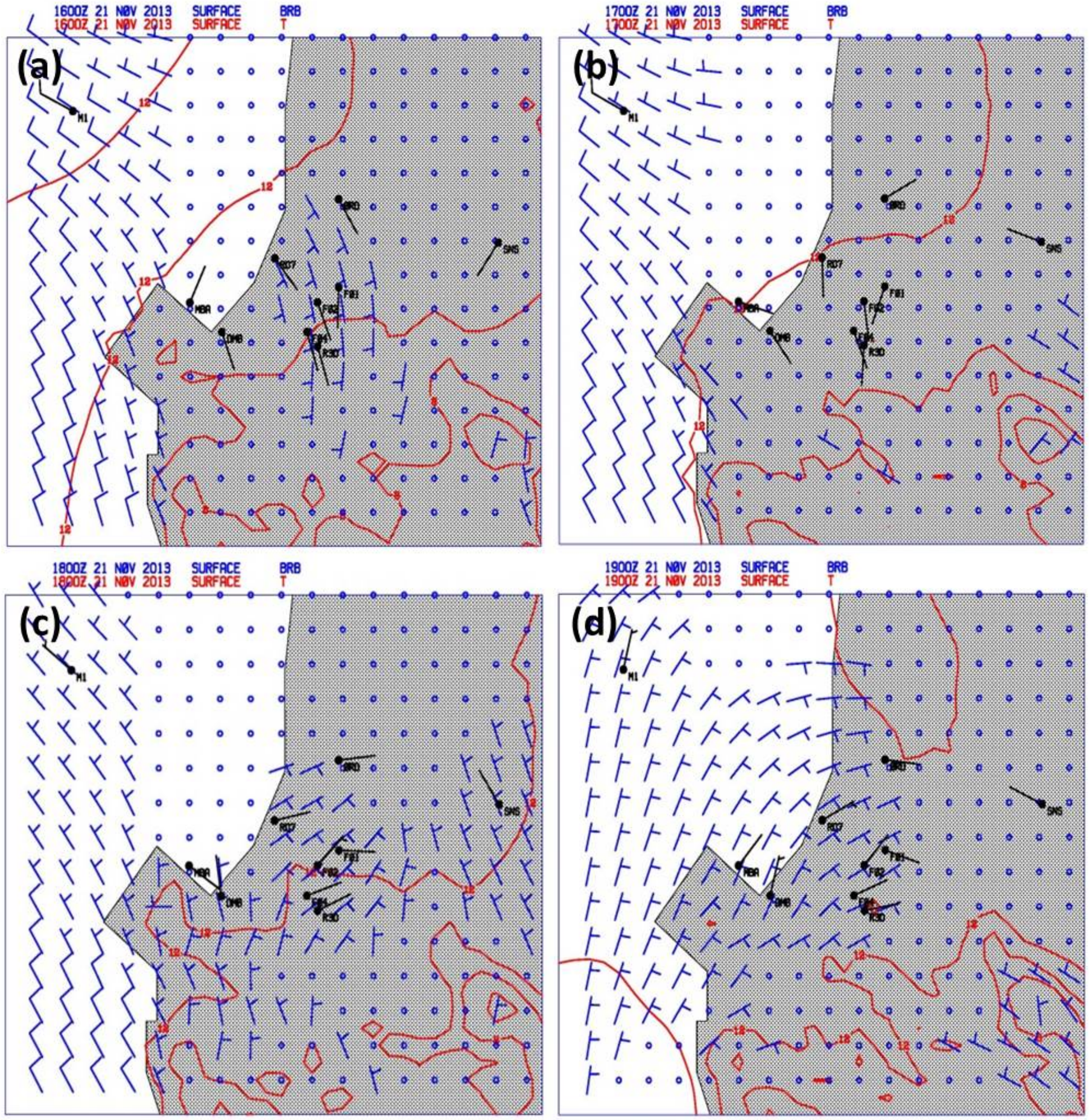
Measurements of virtual temperature and wind on 21 November 2013. Source: Monterey Area Environment, 2015: NPS 915MHz profiler at Fort Ord mixing height: 2003. Accessed 06 April 2015

Figure 38. 850 mb geopotential height and winds



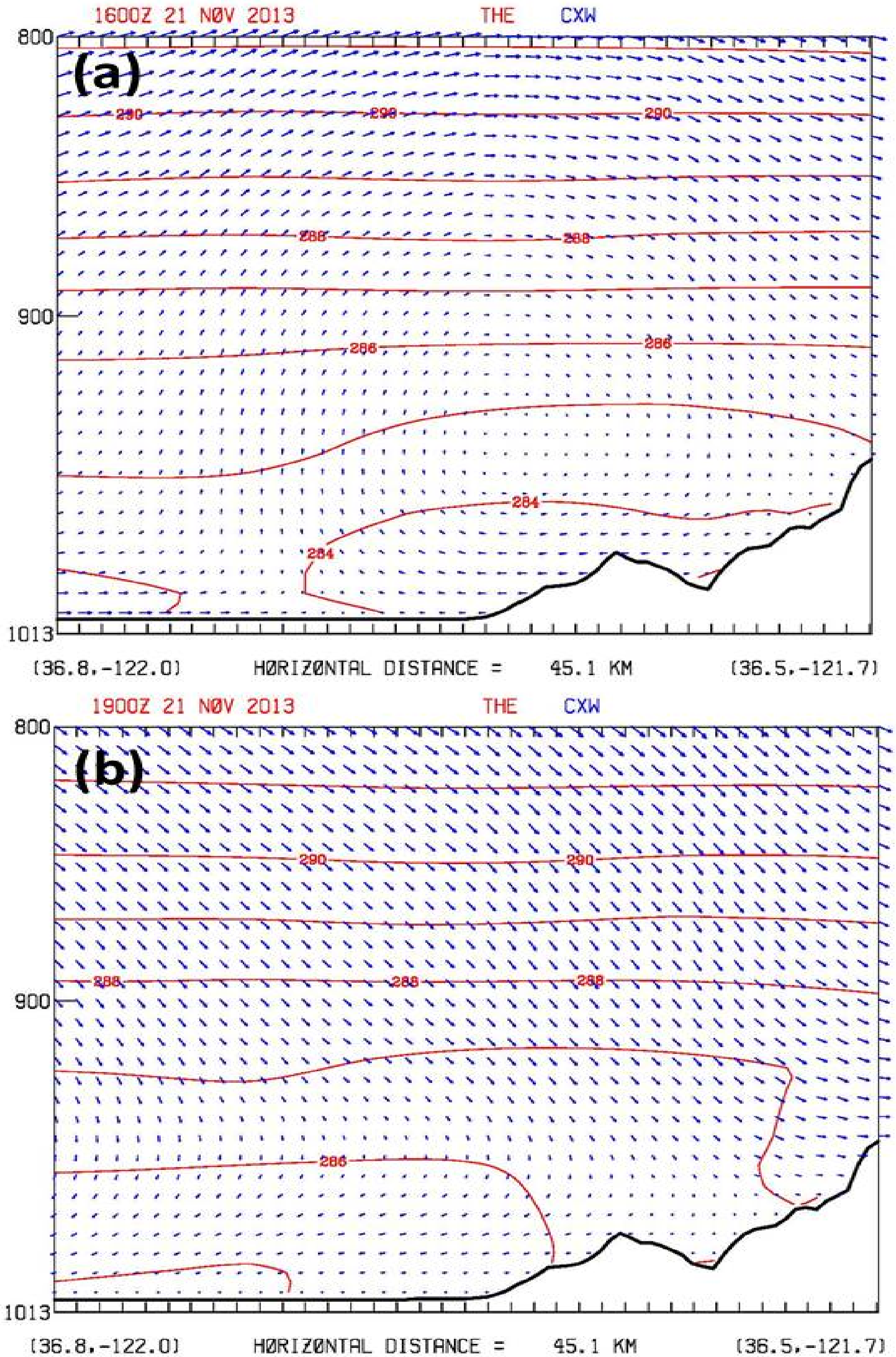
0000 (a), 0600 (b), 1200 (c) and 1800 (d) UTC 21 November 2013

Figure 39. Surface temperature and winds



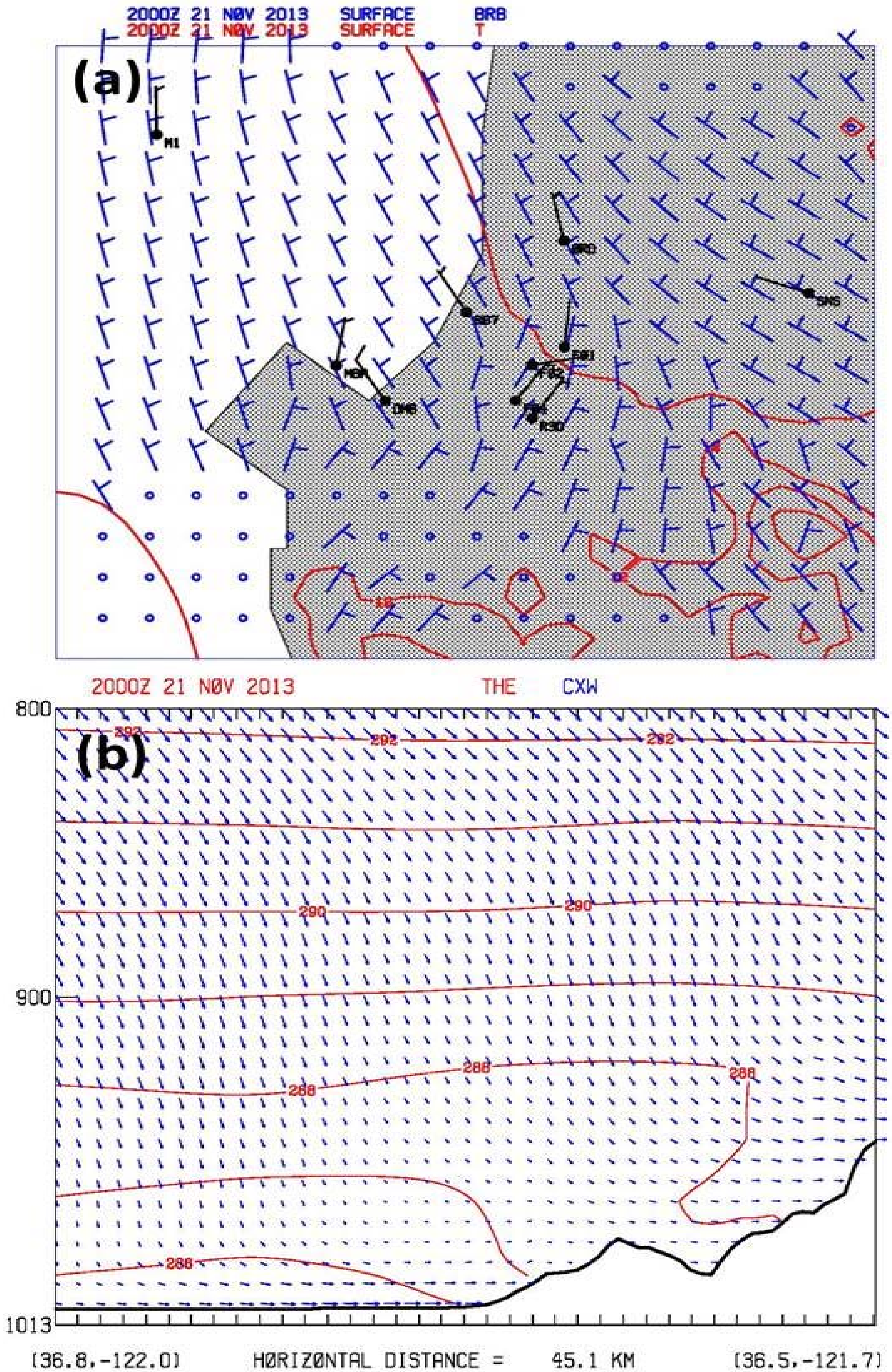
1600 (a), 1700 (b), 1800 (c) and 1900 UTC 21 November 2013

Figure 40. Potential temperature and winds in the plain of the cross section



1600 (a) and 1900 (b) UTC 21 November 2013

Figure 41. Surface and cross section plots



Surface temperature and winds (a) and potential temperature and winds in the plain of the cross section (b) at 2000 UTC 21 November 2014

D. SUMMARY

The 12 cases of flow patterns that resulted in a delayed sea breeze onset over Fort Ord show considerable variability in their characteristics. Synoptic scale flow that produces or evolves into a flow direction capable of providing an opposing cross coast flow speed of 2–5 knots (offshore) was the most likely pattern to delay the sea breeze onset. The offshore component could arise from a variety of synoptic wind directions and speeds. In addition to this primary effect, increased static stability was found to limit vertical motion and thereby delay the sea breeze onset. One case was found where the temperatures were generally cold with a weak thermal gradient resulting in delay of the sea breeze. These results are summarized in Table 3.

Table 3. Delayed sea breeze onset summary of results

Analysis of Delayed Sea Breeze Onset for Fort Ord Prescribed Burning Operations							
Type	Case Study	Synoptic Wind Flow Direction	Synoptic Wind Flow Speed	Cross Sectional Opposing Flow	Cross Sectional Average Thermal Gradient	Sea Breeze Onset Time	Sea Breeze Magnitude
Synoptic Scale Flow	2-Oct-14	Southerly	5 knots	2 knots	4.5°	2000 UTC	5 knots
	3-Oct-14	Southeasterly	5 knots	3 knots	6°	2030 UTC	5 knots
	14-Oct-13	Easterly	5 knots	3 knots	5°	2000 UTC	5 knots
	1-Oct-14	Northeasterly	20 knots	2 knots	5°	2000 UTC	4 knots
	4-Oct-13	Northeasterly	25 knots	1 knots	4.5°	2130 UTC	4 knots
Static Stability	10-Sep-13	Northwesterly	10 knots	0 knots	4.5°	1930 UTC	2 knots
	1-Nov-13	Neutral	5 knots	4 knots	4.5°	1930 UTC	2 knots
Thermal	21-Nov-13	Northerly	10 knots	2 knots	1.0°	2030 UTC	2 knots

Table 3 shows the results of each case study to show their similarities and/or differences. The wind barb and direction of the CFSR 850 mb imagery over the Monterey Bay at 1200 UTC provided the synoptic wind flow direction and speed. The magnitude of the cross sectional wind vector over Fort Ord at 1600 UTC represents the cross sectional opposing flow. The remaining values presented in Table 3 are acquired through utilizing the cross section plots for the time associated with each respective day's sea breeze onset. The potential temperature values at the surface through the 900 mb levels are averaged for a point over Fort Ord and over the Monterey Bay with the resultant difference representing the cross sectional average thermal gradient. The sea breeze onset time was determined when the Fort Ord observations and cross sectional imagery displayed an onshore wind component. Finally, cross sectional surface wind vector magnitude at Fort Ord provides the sea breeze magnitude.

Table 3 shows, for all eight case studies, that the sea breeze onset times were relatively consistent around 2000 UTC with approximately only a 30-minute variation. All the synoptic scale case studies provide a component of offshore flow resisting the development and penetration of the sea breeze. Interestingly, whether the synoptic scale flow was southerly, easterly, or northeasterly, the development of approximately a 5° thermal gradient triggered the sea breeze onset resulting in a magnitude of 5 knots. Static stability cases were not influenced by synoptic scale forcing as vertical motion is inhibited thus thermal gradient development triggered the sea breeze onset. As seen with synoptic scale cases, an approximate 5° thermal gradient triggered the sea breeze onset with a weaker 2 knot magnitude. Lastly, when the temperature of Fort Ord is representative of the Monterey Bay, the absence of a thermal gradient also inhibits sea breeze development. A 1° thermal gradient was sufficient to generate the sea breeze but a weaker 2 knot magnitude onshore flow occurs similar to the static stability cases.

In summary, each delayed sea breeze onset type presents specific pros and cons in considering whether to conduct a prescribed burn. Various synoptic scale directions and speeds promote a delayed sea breeze with a 5° thermal gradient triggering the onset.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This research focused on identifying the background synoptic scale flow and associated delayed mesoscale flow response, characterized the primary sensitivities involved, and developed potential “rules of thumb” in order to increase forecaster accuracy for prescribed burning operations at Fort Ord. Various synoptic scale directions and speeds promote a delayed sea breeze with a 5° thermal gradient triggering the onset. Critical in the synoptic scale flow is to produce an offshore component (southeasterly) over Fort Ord during the sea breeze initiation period. This could be present initially or develop through the day as the synoptic pattern shifts. Cross coast opposing flow of 2–3 knots was sufficient to delay the sea breeze by 3–4 hours.

The sensitivity of the sea breeze onset to the various factors was surprisingly small. The opposing flow was in the 2–3 knot range in nearly all cases so it could not be determined what the response to a 6–8 knot flow might be. In addition, the cross coast thermal gradient of 4–5°C was pretty universal and sea breeze sensitivity seemed very small.

Finally, the results of the study suggest several primary factors to look for in order to predict a delayed sea breeze onset. A southeasterly wind component of 2–3 knots over Fort Ord and a thermal gradient less than 5°C are critical factors to delay the sea breeze. Focusing on the evolution of these factors in the forecast should increase the ability to identify a delayed sea breeze.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Two areas of further research were exposed through these case studies. First, this study was conducted over a two-year period for the months of September through November of 2013 and 2014. Due to the small sample size of potential prescribed burn days provided each year (approximately 5–10), a larger sample size using five to ten years will better sample the parameters that oppose sea breeze onset and help to better address the sensitivity of the sea breeze response to these factors. Idealized modeling approaches applied to the Monterey Bay region would help to better define the sensitivity of the sea breeze response to background synoptic flow direction, static stability, or absolute temperature specific to the region.

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